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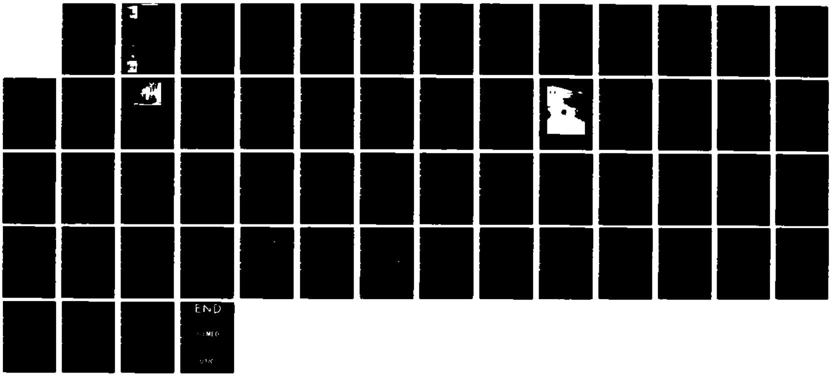

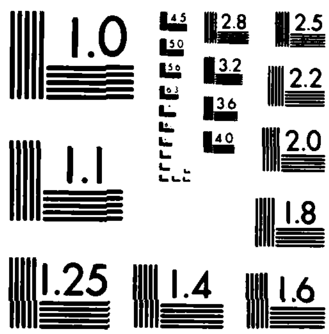

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ENVIRONMENTAL AND WATER QUALITY OPERATIONAL STUDIES

TECHNICAL REPORT E-84-10

INVESTIGATION AND DISCUSSION OF TECHNIQUES FOR HYPOLIMNION AERATION/OXYGENATION

by

Jeffery P. Holland and Charles H. Tate, Jr.

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DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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This report examines elements of the design and operation of hypolimnetic aeration systems. Three basic types of hypolimnetic aerators are identified, and pertinent literature for each is reviewed.

Hypolimnetic aeration with pure oxygen (i.e. hypolimnetic oxygenation) at Clarks Hill Reservoir, Georgia-South Carolina, is overviewed. Included are results of hypolimnetic aeration field tests conducted by contractors

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20. ABSTRACT (Continued).

and the US Army Corps of Engineers at Clarks Hill. Results from these tests showed that, for hypolimnetic oxygenation to most effectively enhance downstream release, most of the input oxygen should be placed (1) within the hypolimnetic withdrawal zone and (2) by a linear diffuser.

A number of hypolimnetic aerator designs are considered. The use of numerical simulation techniques to predict idealized values for aerator design is also discussed. A combination of such results from the Clarks Hill field tests and numerical simulation efforts has produced the initial design for a hypolimnetic oxygenation system at Richard B. Russell Reservoir, South Carolina-Georgia, which is presented herein.

PREFACE

This analysis, conducted by the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES), from September 1981 to August 1982, was sponsored by the Office, Chief of Engineers (OCE), US Army. The effort was initiated under Work Unit IIIB of the Environmental and Water Quality Operational Studies (EWQOS) Program, entitled In-Reservoir Techniques for Improvement of Environmental Quality. OCE Technical Monitors for EWQOS were Mr. Earl Eiker, Dr. John Bushman, and Mr. James L. Gottesman; WES Program Manager was Dr. J. L. Mahloch. Mr. H. B. Simmons, Chief, HL, and Mr. J. L. Grace, Jr., Chief, Hydraulic Structures Division, directed the effort. Messrs. J. P. Holland and C. H. Tate, Jr., conducted the study and prepared the text under the direct supervision of Dr. D. R. Smith, Chief of the Reservoir Water Quality Branch (RWQB), who also reviewed this report.

Commander and Director of WES during this study and the preparation of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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CONTENTS

CONVERSION FACTORS, NON-SI TO METRIC (SI) UNITS OF MEASUREMENT

The non-SI units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	1233.489	cubic metres
acres	40.46873	hectares
Btu (International Table)	1055.056	joules
cubic feet per second (cfs)	0.02831685	cubic metres per second
cubic feet per minute (cfm or SCFM)	0.0004719474	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet/minute	0.005080	metres per second
inches	2.54	centimetres
kilowatt-hours per ton	3968.32	joules per kilogram
miles (US statute)	1.609347	kilometres
pounds	0.435924	kilograms
pounds/minute	0.007559873	kilograms per second
square feet	0.09290304	square metres
square miles (US statute)	2.589998	square kilometres
tons (short, 2000 lb)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

INVESTIGATION AND DISCUSSION OF TECHNIQUES FOR HYPOLIMNION AERATION/OXYGENATION

PART I: INTRODUCTION

Background

1. From late fall to midspring, most US Army Corps of Engineer (CE) reservoirs are generally isothermal. With the onset of warmer weather, water near the surface is warmed and becomes less dense than the cooler waters beneath. Consequently, by late May or June, a pattern of density stratification is generally established. Due to the stratification, transfer of oxygen-rich epilimnion waters into the hypolimnion is inhibited; decomposition of organic matter often causes a gradual reduction of hypolimnetic dissolved oxygen (DO) concentrations resulting in deterioration of hypolimnion waters and the possible onset of anoxic conditions.

2. A number of methods exist to increase the DO concentration of a waterbody. One such method is hypolimnetic aeration. The primary goal of hypolimnetic aeration is to increase the DO concentration of hypolimnetic or bottom waters without weakening or destroying the existing thermal stratification. In this respect hypolimnetic aeration represents a distinct contrast to artificial circulation (destratification) by seeking to maintain both the natural heat budget and a coldwater resource. Aeration of a reservoir, while maintaining the existing pattern of stratification, has a number of benefits including (a) oxygenation of bottom waters which increases pH and lowers the concentration of reduced substances such as Fe^{++}, Mn^{++}, and H_2S; (b) prevention of possible winter and summer fish kills due to anoxic hypolimnetic conditions; (c) enhancement of coldwater fisheries in warmwater climates; and (d) maintenance of downstream water quality requirements through selective withdrawal techniques by preservation of the natural pattern of stratification. Each or all of these benefits are of concern

to specific CE reservoirs, especially those designated for recreation (fishing) and water supply.

Purpose and Approach

3. The purpose of this report is to identify various techniques for the design and operation of hypolimnetic aeration systems. Since the first reported use of hypolimnetic aeration at Lake Bret, Switzerland (Mercier and Perret 1949), a number of different hypolimnetic systems have been devised and field tested. Performance data have been published for many of these systems. Many of these data have not yet been verified, however, and thus no individual system is in widespread use and no general selection, design, or operational guidance has been presented. However, initial guidance on the selection, design, and operation of a hypolimnetic aeration system will be provided by a review of existing techniques for hypolimnetic aeration. This report includes CE experiences with hypolimnetic aeration, considerations for hypolimnetic aerator design, use of numerical modeling techniques for sizing aerator oxygen requirements, and a synopsis of pertinent literature on hypolimnetic aeration (Appendix A). This report commences with an overview of CE experiences with hypolimnetic aeration at Clarks Hill Reservoir.

PART II: CE EXPERIENCES WITH HYPOLIMNETIC AERATION AT CLARKS HILL RESERVOIR

4. A vast amount of hypolimnetic aeration experience within the CE has been obtained during investigation of hypolimnetic oxygenation operations at Clarks Hill Reservoir, Georgia-South Carolina. The US Army Engineer District, Savannah (SAS), initiated a contractual agreement with Dr. Richard E. Speece, Drexel University, Philadelphia, Pennsylvania, which provided for the design and analysis of a hypolimnetic oxygen injection system at Clarks Hill Reservoir. Personnel of the US Army Engineer Waterways Experiment Station (WES) Reservoir Water Quality Branch (RWQB) evaluated the Speece-designed Clarks Hill system in 1977 (Merritt and Leggett 1981) and performed field testing on an additional system based on RWQB guidance in 1978. Based upon the Speece analysis at Clarks Hill (a thorough discussion of the Speece work is available in Speece et al. (1978)), SAS has designed an innovative oxygen injection system for the Richard B. Russell hydropower project (US Army Engineer District, Savannah 1981). This report will review the Speece analysis, the RWQB evaluation, and the SAS design.

Description of Project and Problem

5. The Clarks Hill Project, on the Georgia-South Carolina border, is the first multiple-purpose project completed on the Savannah River. The project, whose damsite is located 22 miles* northwest of Augusta, Georgia, provides flood control, recreation, and hydropower. The hydropower plant houses seven conventional turbines, each having a capacity of 40 mW. The reservoir has a drainage area of 6144 square miles and impounds 1,500,000 acre-ft of water at the bottom of the power pool at an elevation of 312 feet NGVD.

6. At the time of the Speece studies, the reach of the Savannah River just downstream of the Clarks Hill Project was classified a trout

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* A table for converting the non-SI units of measurement used in this report to metric (SI) units is found on page 3.

fishery. A maximum release temperature from the dam of 70° F and a minimum DO of 6 mg/ℓ were desired. During generation at Clarks Hill, the release generally meets the temperature objective; however, Speece et al. (1978) reported that the release failed to meet the DO objectives for approximately 130 days during the stratification season. Thus, supplemental oxygen must be added to the release to meet the DO objective desired for the downstream fishery. Further, this oxygen must be added in a manner that does not excessively warm the reservoir and, subsequently, the downstream release.

1975 Oxygenation Testing at Clarks Hill

7. Speece (1975) found hypolimnetic aeration by pure oxygen injection from an in-reservoir diffuser system to be the most resource-efficient system for Clarks Hill. Speece commenced work in the summer of 1975 with the objective of evaluating pulsed oxygen injection near the dam face. The injection system was to supply oxygen in proportion to the water discharge from one turbine. This was done to check the feasibility of meeting a downstream release DO objective of 6 mg/ℓ and to evaluate the oxygen absorption efficiency of the system. Three oxygen diffuser racks were employed, each rack having 10 1-ft-square diffuser plates located 10 ft on center. The bubbles generated from these diffusers of 2 ft/min permeability were approximately 2 mm in diameter. Each diffuser was loaded at 2400 lb of oxygen per day at 140 ft of submergence. The racks were placed approximately 100 ft from the intake of the operating turbine.

8. Results of the 1975 tests showed that pulsed injection of oxygen adjacent to the penstock intakes with an injection rate matched to the water discharge rate could raise the DO from 2 to 8 mg/ℓ, with an associated absorption efficiency of 85 percent ± 5 percent. However, analysis of these results from operation of the oxygenation system in a pulsed mode showed that the system failed to make use of the economies associated with continuous injection. Consequently, a second field study was recommended to evaluate a continuous injection system located

1 mile upstream from the dam, a distance that corresponded approximately to 4 days travel time to the dam.

1976 Oxygenation Testing

9. The 1976 field tests evaluated diffusers with permeabilities of 10.0, 2.0, and 0.5 ft/min standard permeability and oxygen loading rates of 0.3, 0.6, 1.0, 2.0, and 3.0 actual cu ft O_2/min. Speece installed nine diffuser racks within the reservoir approximately 1 mile upstream from the dam and operated the system nearly continuously for 8 days at a loading of 100 tons O_2/day. From these tests, Speece concluded that three modifications of diffuser placement and operation were necessary to further improve future system performance. First, the racks needed to be placed farther apart to minimize localized destratification of the reservoir. Second, the oxygen injection rate per diffuser needed to be lowered. The original oxygen injection rates and permeabilities (10 ft/min standard permeability, 4 actual cu ft O_2/min) were found to be so high that the bulk of the injected oxygen plume was reaching equilibrium (neutral buoyancy) above the withdrawal zone of the penstocks; further, the system oxygen absorption efficiency of 35 percent was far below the design value of 90 percent. Third, the original 10-ft/min permeability diffusers were replaced with 2-ft/min permeability diffusers since the system displayed more efficient oxygen transfer with the latter.

1977 Oxygenation Testing

10. In 1977, short-term field tests were conducted at Clarks Hill by both Speece and personnel of the RWQB. The continuous system used by Speece injected 100 tons/day of oxygen for 30 consecutive days using nine diffuser racks (40 diffusers/rack). Use of 2-ft/min standard-permeability diffusers loaded at 500 lb O_2/sq ft/day resulted in a 50 percent oxygen recovery rate in the turbine discharges. The bulk of the oxygenated waters still reached equilibrium above the mainstream of the penstock withdrawal zone as discussed for the 1976 tests. In an

effort to correct this problem, Speece placed a 10- by 10-ft baffle deflector 40 ft above the oxygen injection diffusers in order to dissipate the energy of the oxygen bubble plume. Subsequently, the bubble plume reached equilibrium approximately 60 ft lower in the pool than in the previous tests.

11. Concurrent with the 1977 Speece work, members of the RWQB conducted oxygenation field tests at Clarks Hill. Merritt and Leggett (1981) reported that the purposes of the 1977 RWQB work at Clarks Hill were (a) procurement of background data on dissolved nitrogen levels and (b) determination of the effects, if any, of oxygen injection on dissolved nitrogen concentrations in the reservoir. Emphasis was placed on evaluation of the nitrogen-stripping properties that had been hypothesized with oxygen injection.

12. RWQB personnel evaluated the 1977 Speece oxygenation system (without the baffle deflector) in July and August 1977. Dissolved nitrogen concentrations were observed to increase in the vicinity of the injection site; Merritt and Leggett (1981) made no assumptions as to the presence of increased N_2 levels elsewhere in the reservoir. The maximum N_2 concentration observed around the injection site was 111 percent of surface saturation, an increased N_2 concentration which was postulated to come from the release of molecular nitrogen due to denitrification of entrained anoxic bottom sediments in the bubble plume. Depending on operating conditions, the release of molecular nitrogen by this process could overshadow the nitrogen-stripping process. Merritt and Leggett suggested that increased spacing between the diffusers and/or decreased injection rates per diffuser could reduce the probability of the entrainment of bottom sediments in the bubble plume.

1978 Oxygenation Testing

13. After the 1977 studies, both Speece and RWQB, acting independently, concluded that a linear diffuser design, rather than the square diffuser design tested previously, might alleviate the problems encountered in the 1977 tests while pumping the required oxygen rate.

The intent of this design was to spread the injected oxygen across the lake and provide less energy to the plume than the square diffuser racks. Speece tested a 40-ft-long linear diffuser system which was assumed to approximate a section from a larger linear system. Comparing the performance of the 1977 diffuser design with this linear system prompted Speece to recommend that a 2000-ft-long linear diffuser system, capable of providing 100 tons O_2/day, be positioned 10 ft off the reservoir bottom. The spacing of the individual diffuser plates would be 1 ft on center, yielding a loading rate of 500 lb O_2/sq ft/day. In addition, Speece speculated that a baffle deflector system (a carryover from the 1977 studies) could be developed to ensure that the oxygen be injected at the proper position within the penstock withdrawal zone.

1978 Field Testing of RWQB Oxygenation System

14. Concurrent with the Speece work at Clarks Hill, an investigation of hypolimnion aeration/oxygenation was initiated at WES as part of the Environmental and Water Quality Operational Studies (EWQOS) Program. Evaluation of existing systems and literature, as well as coordination with various Federal agencies, led RWQB personnel to conclude that a linear diffuser system was a more efficient design for placement of oxygen in a given penstock withdrawal zone than the other designs investigated. Consequently, RWQB conducted a short-term field demonstration of a 100-ft-long linear diffuser design for SAS at Clarks Hill Reservoir during the summer of 1978.

15. The system investigated by RWQB was 100 ft long and had 1-ft-square diffuser plates placed 10 ft on center. Each plate floated 5 ft above a 3-in. steel header pipe and was connected to the pipe with 1/4-in. flexible tubing. The diffuser plates were ceramic plates identical to those used by Speece in 1977, and oxygen was supplied through flow lines and controls used for previous Speece work. (A schematic of the system is shown in Figure 1.) The test system was designed to be assembled by two people working in the water and on a floating platform (Figure 2). Following assembly, the system was installed at

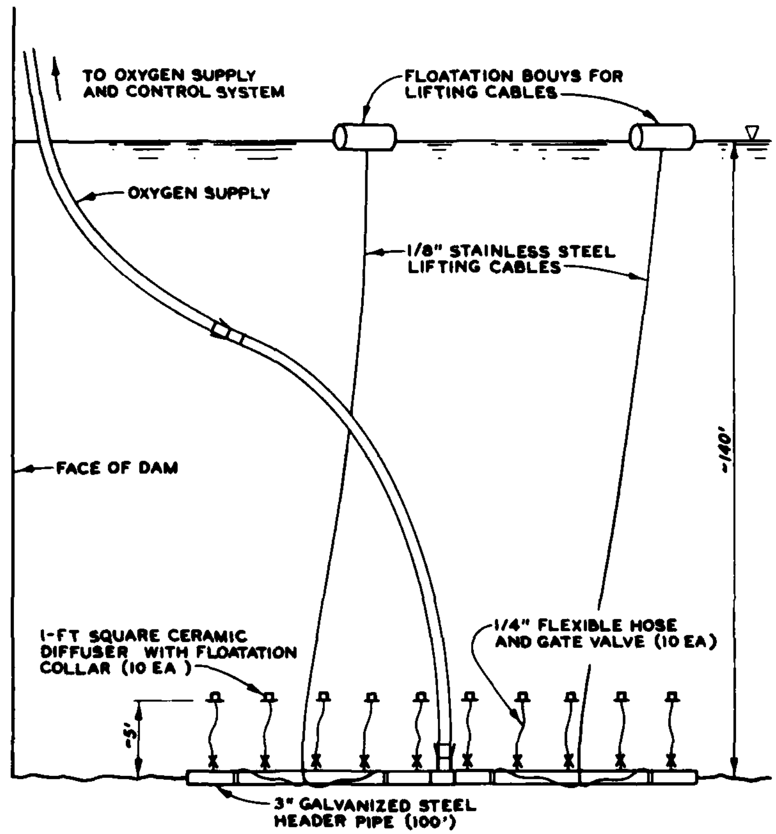


Figure 1. Oxygen injection system demonstrated by RWQB at Clarks Hill, S. C., 1978 (not to scale)

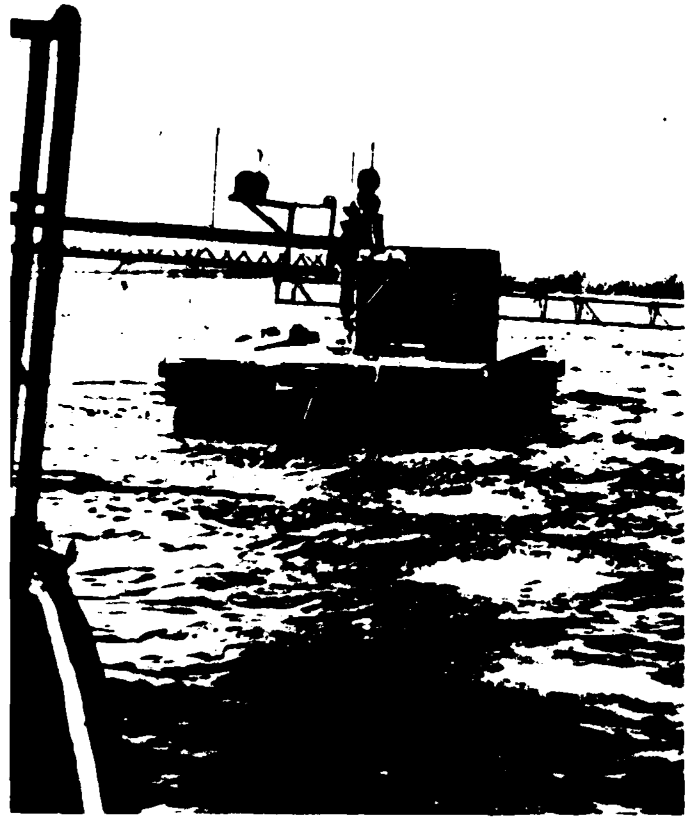


Figure 2. Installation of oxygen injection demonstration system at Clarks Hill, S. C., 1978

the lake bottom just off the face of the dam. The integrity of the system was then validated and final adjustments made.

16. The primary objective of these tests was to develop design guidance for an injection system with a given injection rate such that the bulk of the absorbed oxygen reached equilibrium within the penstock withdrawal zone. The location of these withdrawal zones was evaluated by computing the normalized velocity profile in the reservoir for a given stratification. While the normalized velocity profile does not relate actual volumes of withdrawal from the reservoir, it does show the upper and lower limits of withdrawal and the point of maximum withdrawal velocity. With predictions of these locations, the ability of an injection system to place oxygen within this withdrawal zone for given injection rates can be evaluated. The normalized velocity profiles given herein were predicted using a set of transcendental equations developed at WES to describe withdrawal from density-stratified lakes and reservoirs. The equations used for this report were determined from a hybrid model study of Richard B. Russell Reservoir (Smith et al. 1981) that uses an outlet design very similar to that at Clarks Hill.

17. Dissolved oxygen (DO) data were taken approximately 1.5 miles upstream from the dam on 31 July 1978 in order to obtain background data which were not biased by previous field tests conducted by Speece et al. (1978). Testing of the RWQB system began on 1 August 1978. The objective of these tests was to demonstrate the ability of a linear diffuser system to place injected oxygen in a predicted penstock withdrawal zone. Oxygen injection commenced at midnight and concluded 8 hr later because this period afforded the longest continuous injection period possible without disturbance of the test "steady-state" conditions by hydropower operations.

18. After each 8-hr injection period, DO profiles were determined at the three sampling stations shown in Figure 3. Attempts were made to sample each of the stations for each test. Unfortunately, commencement of hydropower operations precluded data acquisition at one or more of the stations for several tests. The DO profiles obtained

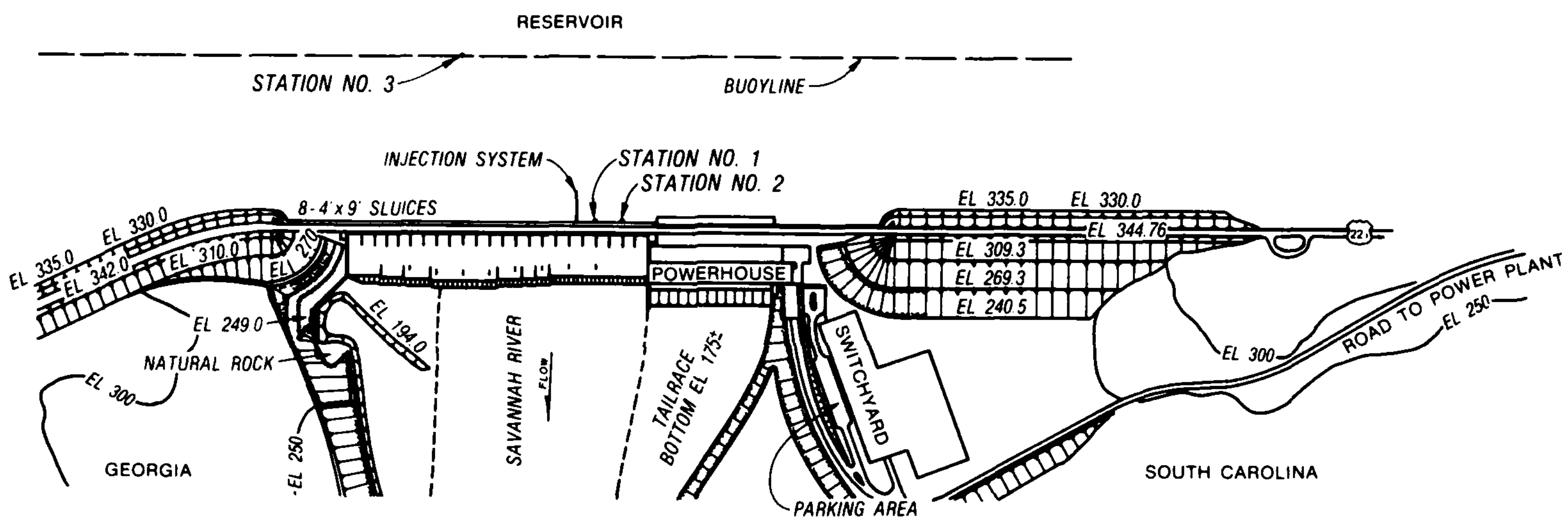


Figure 3. Location of three sampling stations used during testing of RWQB oxygen injection demonstration, 1978

for oxygen injection rates ranging from 868 to 1670 lb O_2/1-ft-square diffuser/day are given in Figure 4 along with the normalized velocity and temperature profiles for the given test and date.

19. As indicated in Figure 4, the linear diffuser system was quite effective in placing injected oxygen within the predicted penstock withdrawal zone, the limits of which are at depths of approximately 8 and 42 m as shown by the predicted normalized velocity profile. Within the range of oxygen injection rates investigated, as the injection rate increased the elevation of the injected DO was moved higher in the pool. However, the injected oxygen generally remained well within the predicted penstock withdrawal zone for all injection rates tested. As shown in Figure 4, almost no change in DO concentration above the background was noted outside the predicted withdrawal limits. Further, observed surface temperatures in the bubble plumes indicated that little change in epilimnetic temperatures occurred during these tests (for example, for an injection rate of 1670 lb/sq ft/day, temperatures in the plume ranged between 26.5° and 27.5° C). These measurements indicate that, for the injection rates reported, little, if any, transport of hypolimnetic waters into the epilimnion occurred during the operation of this linear diffuser system, an apparent "uncoupling" of entrained hypolimnetic waters from the bubble plume before the plume passes through the thermocline, which is essential for the maintenance of density-stratified conditions in a reservoir during oxygen enhancement. In addition, the energy of the plume was so dissipated upon its arrival at the surface that generally minimal surface disturbance was observed. An example is shown in Figure 5 for an injection rate of 1670 lb O_2/sq ft/day.

20. Thus, even at the highest injection rates tested, the linear injection system was generally effective at placing oxygen within the penstock withdrawal zone with minimal destratification and surface disturbance. These three characteristics (effective oxygen placement, minimal destratification, and minimal surface disturbance) indicate that the linear configuration for oxygen injection systems is a very attractive alternative for the oxygenation of hypolimnetic waters.

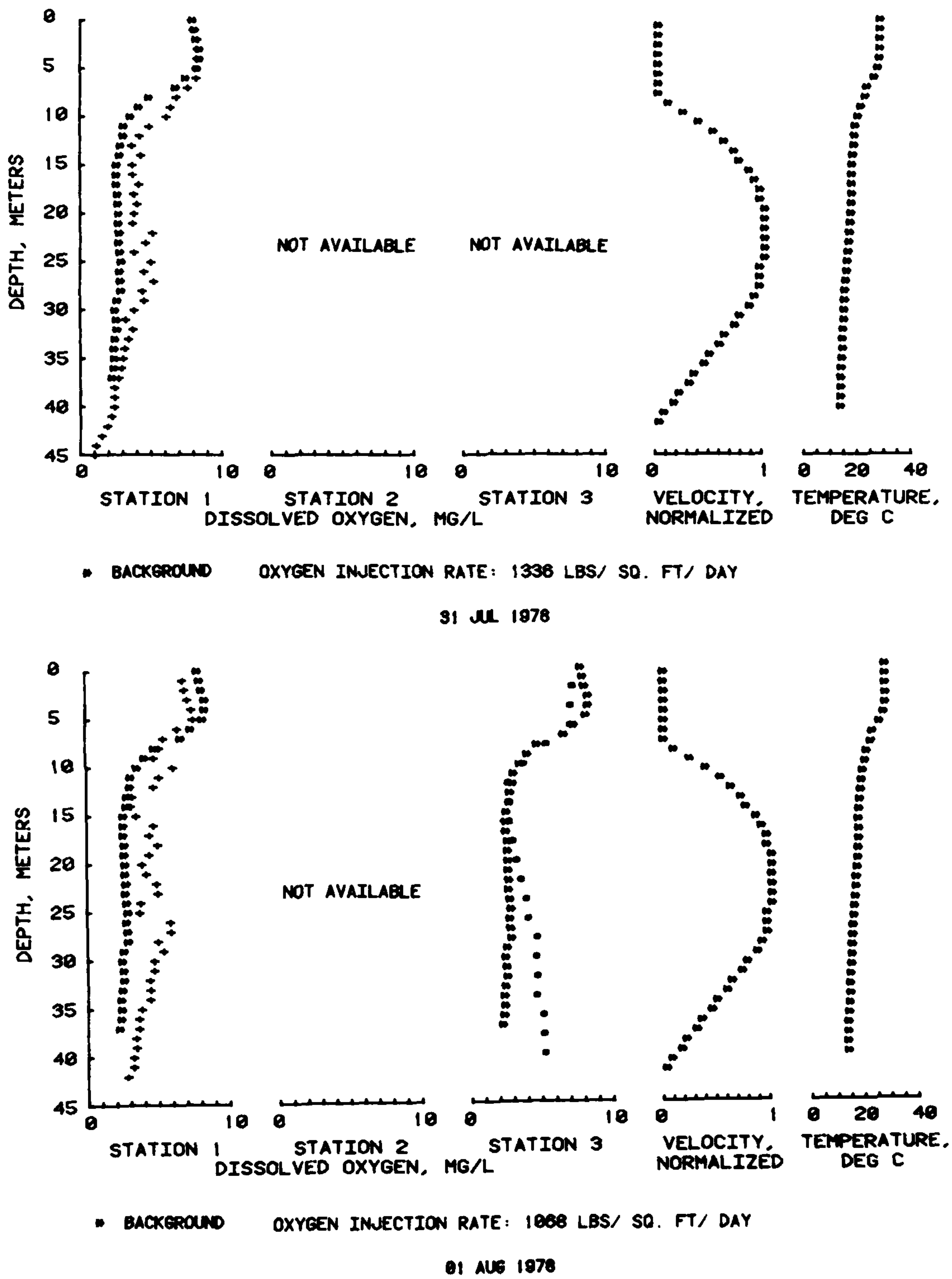
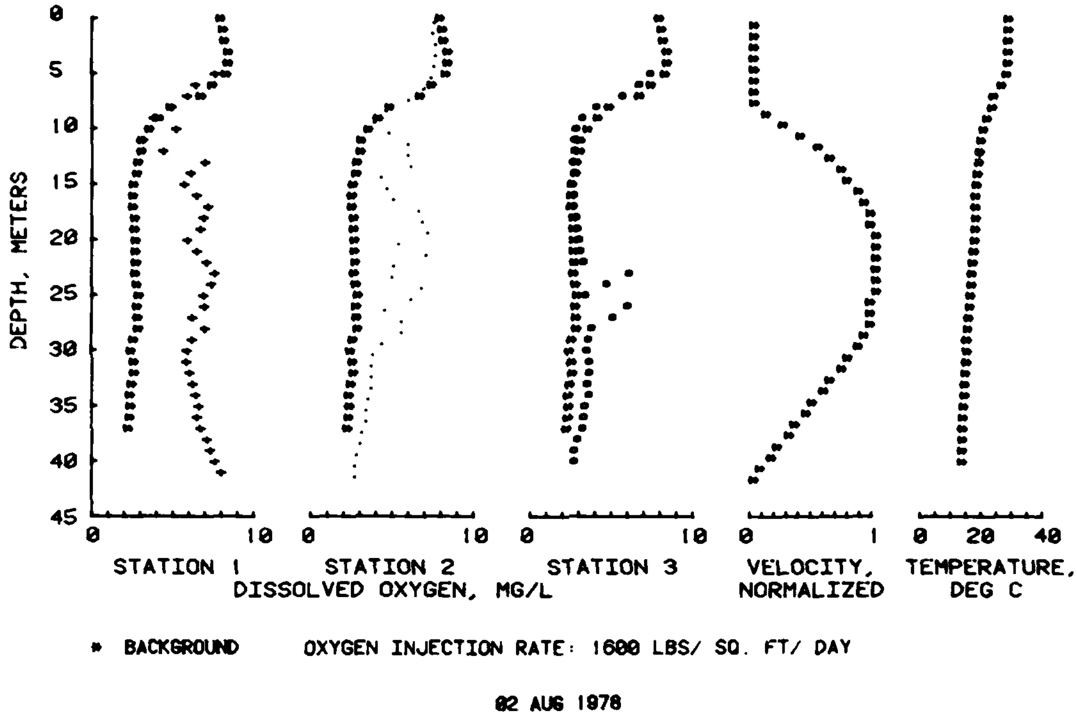


Figure 4. Observed dissolved oxygen and temperature profiles and predicted normalized velocity profiles for oxygen injection rates and dates shown during the RWQB tests at Clarks Hill Reservoir (Sheet 1 of 3)



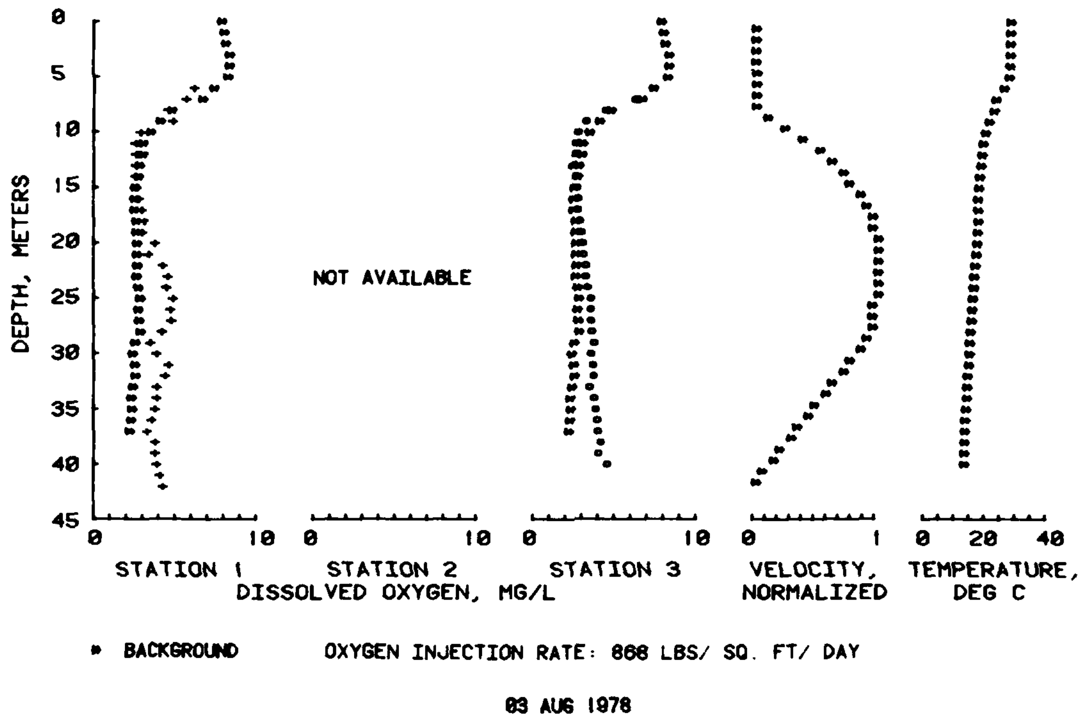
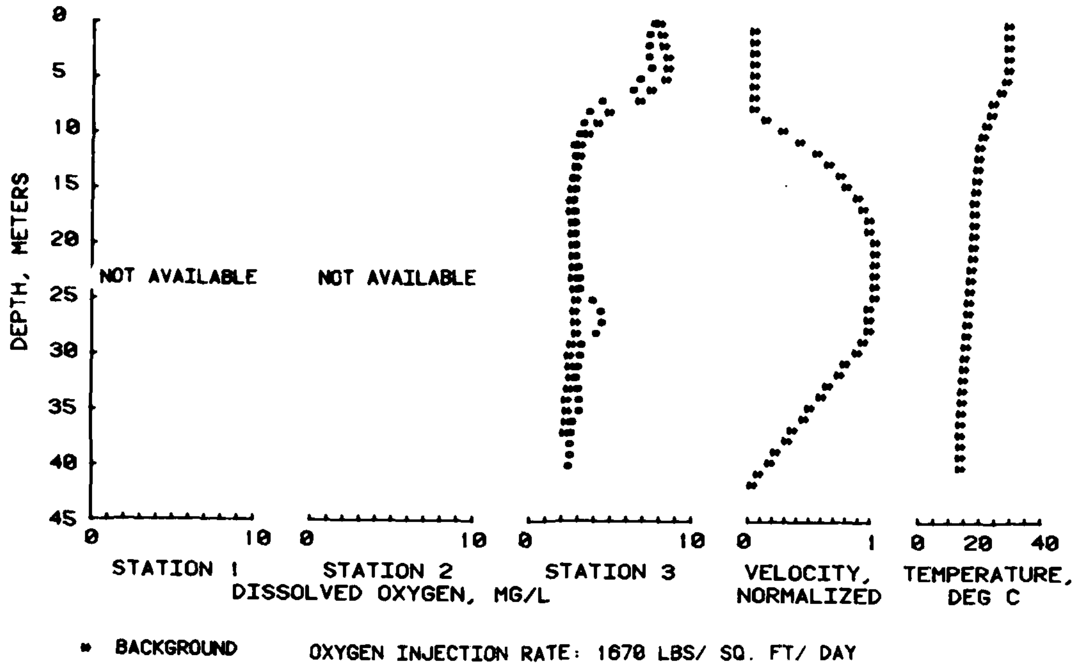


Figure 4. (Sheet 2 of 3)



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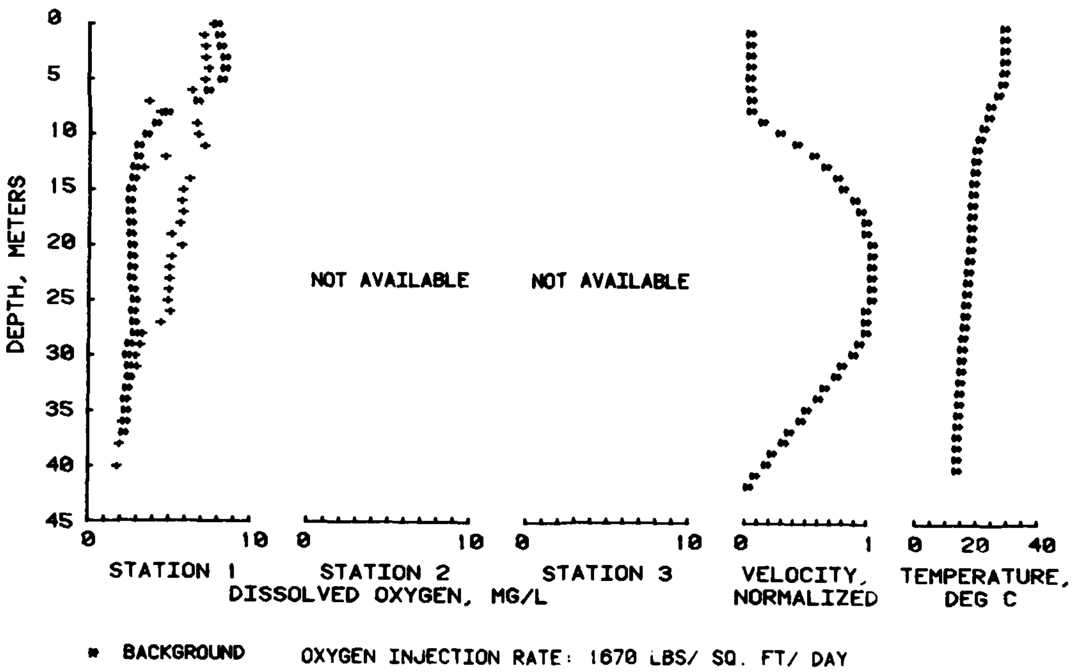

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Figure 4. (Sheet 3 of 3)

Figure 5. Surface disturbance for operation of oxygenation system with an injection rate of 1670 lb O_2/sq ft/day

Oxygen Injection System at Richard B. Russell Reservoir

21. SAS will install a hypolimnetic oxygen injection system into Richard B. Russell Reservoir (RBRR), a multipurpose project nearing completion just upstream of Clarks Hill Reservoir, in order to meet a water quality objective of 6 mg/ℓ O_2 in the downstream release. Based upon the Speece work just described at Clarks Hill (which has hydrodynamic and meteoreological conditions similar to RBRR), and upon a numerical simulation at WES of the expected thermal and oxygen distributions of RBRR (Smith et al. 1981, see also Part IV of this report), SAS has designed an oxygen distribution system consisting of a continuous-feed oxygenation component and a pulse-feed oxygenation component. The system has been designed for an average daily design discharge of 12,500 cfs and a travel time of 4 days for oxygen injected approximately 1 mile upstream of the RBRR dam. The design discharge of 12,500 cfs, which is greater than the average daily discharge over 90 percent of the time, was predicted by operational simulation of the Hartwell-RBRR-Clarks Hill System (Hartwell Dam releases into the headwaters of RBRR). System oxygen demands for the period of required oxygenation (1 June-30 October) were computed based on the previously mentioned design discharge, an oxygenation system absorption efficiency of 75 percent, and a DO objective of 6.0 mg/ℓ. A maximum predicted oxygen demand of 171 tons/day was computed for the period 1-15 October. The continuous-feed component will be located approximately 1 mile upstream of the dam and will have 2160 7-in.-diam round diffusers, each located 1 ft on center. The pulsed-feed component will be located just upstream of the power intakes and will have 1728 7-in.-diam diffusers located 1 ft on center. Each of the diffusers will have a permeability of 2.0 ft/min. A complete discussion of the selection, construction, and operation of the RBRR injection system is provided in Design Memorandum 35 (US Army Engineer District, Savannah, 1981). Additional considerations for the design of hypolimnetic aeration systems are presented in the next section.

PART III: CONSIDERATIONS FOR HYPOLIMNETIC AERATION SYSTEM DESIGN

22. As indicated in Appendix A, there is a wide range of hypolimnetic aerator designs. Unfortunately, most of these systems are experimental in nature and apparently were designed with little theoretical analysis. Taggart and McQueen (1982) have presented an empirically derived model for use in designing hypolimnetic aerators which seeks to maximize flow efficiency. However, the model may not maximize oxygen transfer efficiency, a variable the authors note is difficult to measure. Further, while the model results do agree reasonably well with observed hypolimnion aeration data, the model's empirical derivation may limit applicability. Thus, limited guidance concerning the theoretical hydraulics, gas transfer, and mixing aspects of these systems is available.

23. One of the few extensive efforts to describe an approach for the design of hypolimnetic aeration devices (other than proprietary systems) was presented by Lorenzen and Fast (1977). Although their approach is simplified, it does point out a number of design considerations for these systems. Proper aerator design requires evaluation of potential problems as well as acquisition and analysis of site-specific data. The following is an overview of these considerations.

Potential Problems in Hypolimnetic Aeration

24. Several authors (Lorenzen and Fast 1977; Tolland 1977; Pastorok, Lorenzen, and Ginn 1982) have stated potential problems with hypolimnetic aeration. Those most significant are discussed below.

Unintentional thermal destratification

25. During hypolimnetic aeration, some mixing of epilimnetic and hypolimnetic waters generally occurs. As the objective of hypolimnetic aeration is to maintain the existing lake thermal structure, little mixing is desired. The tabulation below (Pastorok, Lorenzen, and Ginn 1982) shows the warming of hypolimnetic waters in several systems which

Lake	Change in Temperature of Hypolimnion, °C
Waccabuc, N. Y.	0
Mirror, Wisc.	+3
Larson, Wisc.	0
Järlasjön, Sweden	+1
Wahnbach, West Germany	+4
Ottoville Quarry, Ohio	+5

resulted from some mixing of epilimnetic and hypolimnetic waters during hypolimnetic aeration. If proper precautions are not instituted to control this mixing, the waterbody may be destratified by the hypolimnetic aeration mechanism. Fast (1971) caused Hemlock Lake, Michigan, to destratify early while using a full air lift system because his system leaked water. Attica Reservoir, New York, was destratified rapidly by side-stream pumping (Fast 1973b). This was probably due to an improperly designed exit velocity from the discharge pipe which acted to destratify the water by jet mixing.

Underestimation of required aeration capacity

26. Underestimation of the required aeration capacity may occur due to underestimation of the lake's oxygen consumption rate or overestimation of the percentage of oxygen pumped which will dissolve in the water column with a given design. Lorenzen and Fast (1977) suggest, in any case, that the aeration system be sized larger than required based on best estimates. Care, however, must be taken with a larger system to ensure that unintentional destratification does not occur.

Nitrogen gas (N_2) supersaturation

27. The use of compressed air at depth in certain hypolimnetic aerators may result in N_2 supersaturation of the water with respect to surface hydrostatic pressure. Fast, Dorr, and Rosen (1975) point out, for example, that the LIMNO aeration system can cause N_2 supersaturation in the hypolimnion greater than 150 percent relative to surface pressure. Speece (in Lorenzen and Fast 1977) states that even full air lift systems may cause N_2 supersaturation, though Lorenzen and Fast (1977)

doubt this. However, since small increases in N_2 concentration or in temperature may result in N_2 supersaturation with respect to surface pressure, and some hypolimnetic temperature increase is often observed with hypolimnetic aeration, N_2 supersaturation may be a probable concern for certain hypolimnetic aeration designs.

Water-surface fluctuations

28. Severe fluctuation of water-surface levels may reduce the efficiency of many hypolimnetic aerators. Though some of the systems are designed with telescoping or retractable parts, the majority of these systems are fixed for economic reasons. Thus, significant changes in the pool elevations may result in pool conditions incompatible with efficient aeration for the system design initially selected.

Data Requirements for System Sizing

29. Many of the problems described above are the result of improper evaluation of the data inputs described in this section. Certain data are required for the sizing of any hypolimnetic aeration system. Although these data generally result from combination of site-specific meteorological, operational, and hydrological data, aerator sizing requirements usually include at least (a) monthly oxygen and temperature profiles, (b) determination of project volume as a function of depth, (c) project geomorphology, and (d) determination of project withdrawal characteristics. Smith (1984) has provided guidance on the computation of the zone of withdrawal as a function of outflow rate and density structure. Lorenzen and Fast (1977) have described several other important data requirements for hypolimnetic aerator sizing. These descriptions appear below.

Hypolimnetic volume estimates

30. Water volumes within any depth interval are generally calculated from a bathymetric map as discussed by Welch (1948). Volume estimates for each 5-ft (or less) depth interval are desirable. The volumes of respective depth intervals will be used to calculate oxygen depletion rates. The total volume of the hypolimnion is also required

and can be estimated from the volume-depth relationships and temperature profile data.

31. The hypolimnetic volume can be estimated by reviewing a set of temperature profiles during summer stratification. These profiles must be interpreted in order to account for thermocline erosion during aeration. Increases in hypolimnetic volume during aeration due to thermocline erosion have been observed by Fast (1975). Since most reservoir basins are funnel-shaped, a difference of only a few metres in hypolimnetic depth can represent a very large increase in the volume of water which must be circulated and aerated during hypolimnetic aeration. In many cases, the hypolimnetic volume during aeration may exceed the nonaerated hypolimnetic volume by 50 percent or more. If this situation is not considered, the aeration system may be undersized and inadequate.

Oxygen consumption rates

32. The most accurate estimates of hypolimnetic oxygen consumption are derived from observing the rate of oxygen depletion following the onset of thermal stratification. The hypolimnetic oxygen depletion rate following thermal stratification in the spring-summer is preferable. These methods are limited to one or two periods of the year. These periods can be very short in those lakes with high depletion rates. If the lake is monomictic (i.e. has one overturn per year), there will be only one brief opportunity to observe the oxygen depletion rates.

33. The rate of oxygen depletion is calculated by first determining the initial oxygen concentration.

$$\text{Total hypolimnetic oxygen content} = \sum_{i=1}^{n} V_i C_i$$

where

n = number of depth intervals within hypolimnion

V_i = water volume in the i^{th} depth interval, cu ft

C_i = oxygen concentration in the i^{th} depth interval, lb O_2/cu ft

34. The total hypolimnetic oxygen content is then plotted against time. The depletion rate is calculated from the slope of a regression line through selected data points. Generally, the points which give a maximum depletion rate are chosen. The rate of depletion is concentration dependent and decreases as the hypolimnetic oxygen content approaches zero later in the stratification season.

35. This method underestimated by 30 percent the oxygen consumption rate during hypolimnetic aeration of Lake Waccabuc, New York. The oxygen depletion rate was about 2.1 mg/ℓ/week during the spring prior to aeration, but the lake consumed 3.0 mg/ℓ/week during steady-state aerated conditions and hypolimnetic oxygen concentrations of 4.0 mg/ℓ. Overholtz (1975) found closer agreement between oxygen depletion rates in Ottoville Quarry, Ohio, and oxygen consumption during aeration; depletion rates averaged 1.3 mg/ℓ/week, while consumption rates were 1.0 mg/ℓ/week. However, Smith, Knauer, and Wirth (1975) found that the consumption rate in Larson Lake "...during aeration was as much as three to four times as great as the normal depletion rate." Factors which could account for greater oxygen consumption during aeration include: (a) increased water-circulation-induced renewal of the mud-water interface, with subsequent increases in oxygen demand; (b) vertical mixing of sediments and benthic organisms; and (c) increased respiration and decomposition due to temperature increases. Hypolimnetic aeration has caused temperature increases ranging from a few degrees (paragraph 25) to more than 9° C (Appendix A, paragraph 13).

36. Hypolimnetic oxygen depletion rates without aeration can vary considerably from year to year within a given lake. For example, depletion rates at Lafayette Reservoir, California, ranged from 0.35 to 0.82 mg O_2/ℓ/week. Values for nearby San Pablo Reservoir were much more uniform (0.38 to 0.44 mg/ℓ/week). Smith, Knauer, and Wirth (1975) observed substantial variation in oxygen depletion rates without aeration in both Mirror and Larson Lakes, Wisconsin. This variation was greatest in Larson Lake, where depletion rates (without aeration) ranged from 0.08 to 2.31 mg O_2/ℓ/week. Furthermore, if the oxygen depletion is measured for only one season, then the amount of yearly variability

is unknown. In these cases, ample allowance should be made for both yearly variation and for possibly increased consumption during aeration.

37. Cornett and Rigler (1979) have shown a second method for predicting hypolimnetic oxygen depletion rates. These investigators have shown that areal hypolimnetic oxygen deficit is a function of the average thickness and temperature of the hypolimnion during summer stagnation and lake phosphorus retention. This method could be used to assess the necessary oxygen input from aeration.

Oxygen input capacity

38. Lorenzen and Fast (1977) note that the oxygen input capacity will depend on (a) desired oxygen concentration and (b) expected oxygen consumption rate during aeration. In some cases, hypolimnetic aeration may be successful even though it does not increase the hypolimnetic oxygen concentration above zero. Lake Brunnsviken in central Stockholm, Sweden, is a case in point. During winter and summer stagnation, large amounts of hydrogen sulfide accumulated in the deep waters. This gas was vented to the atmosphere at spring and fall overturns to the annoyance of the surrounding inhabitants and businesses. Hypolimnetic aeration of Brunnsviken has prevented the accumulation of hydrogen sulfide in the lake, even though the hypolimnion still has no oxygen; a larger system would be required in order to maintain oxygen above zero. If iron and manganese are a problem, then oxygen concentrations above 2 mg/ℓ should prevent these substances from coming into or remaining in solution (Bernhardt 1974).

39. In practice, it is often desirable to oversize the aeration system to allow for unforeseen variations in oxygen consumption rates, hypolimnetic volume increases, temporary equipment shutdown, or other factors. For example, if the observed rate of oxygen depletion is 3.5 mg/ℓ/week and the hypolimnetic volume is 2000 acre-ft, then the oxygen depletion rate is 1.9 lb/min. It might then be desirable to size an aeration system to inject between 2.5 and 3.0 lb O_2/min at the desired maintenance oxygen concentration (the maintenance level is important since the efficiency of most aerators is dependent on the ambient oxygen concentration). The added costs to oversize a system

are generally a small portion of the total capital costs. If the system is over capacity, then it may not need to operate continuously; intermittent operation of the oversized system may result in satisfactory oxygen levels and operating costs comparable to the continuous operation of a smaller system.

40. Lorenzen and Fast (1977) also presented simplified guidance on airflow requirements and compressor sizing. This guidance and the discussion just presented recommend that hypolimnetic aerators be designed for a "worst case," i.e., to inject the maximum oxygen required to supplement an in-lake condition in order to meet a specified oxygen criterion or standard. This worst case is contingent on a specific set of meteorological, hydrological, and chemical conditions over a particular time frame. However, while the maximum oxygen requirements may be assumed to exist for a particular period (such as late summer), actual conditions in a lake could upset this assumption. A numerical simulation model which incorporates algorithms for both the simulation of water and heat budgets and the prediction of vertical oxygen and temperature profiles can be used to evaluate the oxygen requirements for a hypolimnetic aeration system. Such a procedure is discussed in the next section.

PART IV: USING A NUMERICAL SIMULATION MODEL TO COMPUTE SUPPLEMENTAL OXYGEN REQUIREMENTS

41. In most instances, maximum oxygen requirements in a reservoir are contingent on a specific set of meteorological, hydrological, and chemical conditions. Since the evaluation of oxygen requirements in a reservoir may be necessary over an extended time frame, intensive data collection and evaluation may prove resource exhaustive. However, the use of numerical and/or physical modeling techniques to predict the expected oxygen requirements will provide practical guidance toward the design of a hypolimnion aeration device. A number of numerical models exist which can be used to simulate the reservoir oxygen and temperature distributions. The procedure for using a given numerical model to estimate the oxygen requirements for a hypolimnetic aerator generally entails the following:

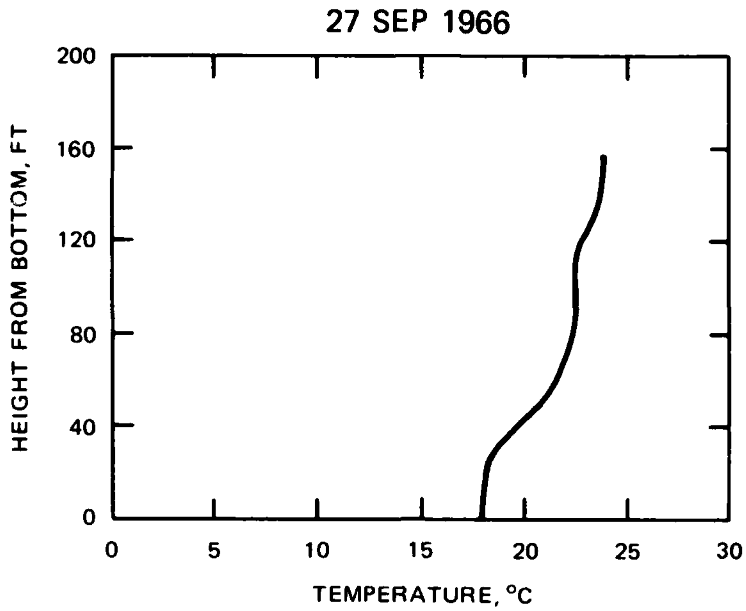
- a. Simulate the vertical oxygen and temperature distributions in the reservoir over a given time frame using specific meteorological, hydrologic, and chemical data.
- b. Define an oxygen criterion to be met with the aeration system, i.e., the minimum DO concentration throughout the hypolimnion or minimum DO concentration desired in the release from the reservoir.
- c. Compute the required oxygen supplement needed to meet the assigned oxygen criterion based on idealized conditions.
- d. Compute (1) oxygen required for injection based on c and (2) system oxygen transfer efficiency.

The critical phase of this procedure in the context of this report is the simulation of the thermal and oxygen distributions in the reservoir. Smith et al. (1981) have used a similiar approach to size an oxygen injection system. An overview of this work is presented in the following paragraphs.

42. Smith et al. (1981) used a numerical model to size a linear oxygen injection system for four in-reservoir alternatives involving modifications of an existing cofferdam at Richard B. Russell Reservoir (RBRR). Only the results from the simulation of the existing project

with the cofferdam removed will be presented here since the evaluation of each in-reservoir alternative or DO enhancement followed the same procedure. The model selected by Smith et al. was WESTEX (Loftis 1980), a thorough description of which can be found in Smith et al. (1981) or Dortch et al. (1976). Smith et al. used meteorology, inflow quantities, and hydropower operations schedules for 4 study years (1955, 1958, 1966, 1967) to simulate the thermal and water budgets in the lake. Three basic assumptions were made: (a) the inflow into RBRR was approximately saturated with dissolved oxygen (DO), (b) the epilimnion was 80 percent saturated with DO, and (c) the depletion rate in the metalimnion and hypolimnion was 0.1 mg/ℓ/day. The inflow assumption was based upon field data; the latter two assumptions were based upon the Fontane and Bohan (1974) analysis of field data obtained from reservoirs immediately upstream (Hartwell) and downstream (Clarks Hill) of the proposed RBRR. Fontane and Bohan demonstrated the validity of these assumptions in numerical simulations of Hartwell and Clarks Hill. After the model had been calibrated, it was used to simulate the period March through October for each of the 4 study years, because this is the period when stratification will most affect water quality at RBRR. Output from these simulations included vertical temperature and oxygen profiles for selected days (Figure 6), release water temperature and DO for each day of the simulation period, and idealized oxygen injection requirements for each day of the simulation period.

43. Results from the modeling effort showed that, typically, the release DO from RBRR was 6 mg/ℓ or less between mid-May and October (Figure 7). In order for the reservoir to release water that has an average DO of 6 mg/ℓ, oxygen would have to be injected into the withdrawal zone in the reservoir during periods when the volumetrically weighted average DO in the release was less than 6 mg/ℓ. Therefore, the idealized daily average injection rate required to eradicate deficits below 6 mg/ℓ was computed by multiplying the average daily release by the portion of the volumetrically weighted average DO below 6 mg/ℓ (the absorption and transport efficiencies of the oxygenation system were "idealized" to be 100 percent). Idealized daily average injection



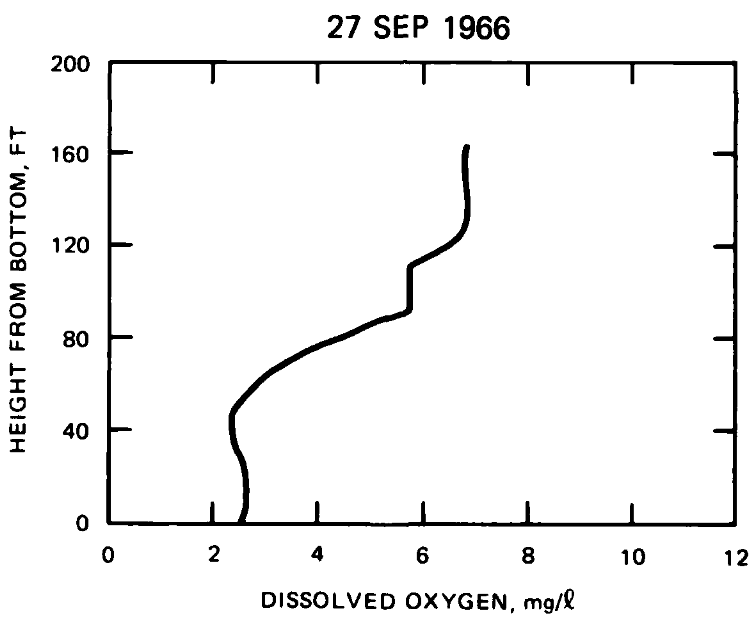


Figure 6. Predicted in-reservoir temperature and DO profiles, 27 Sep 1966, RBRR, Ga. (Smith et al. 1981)

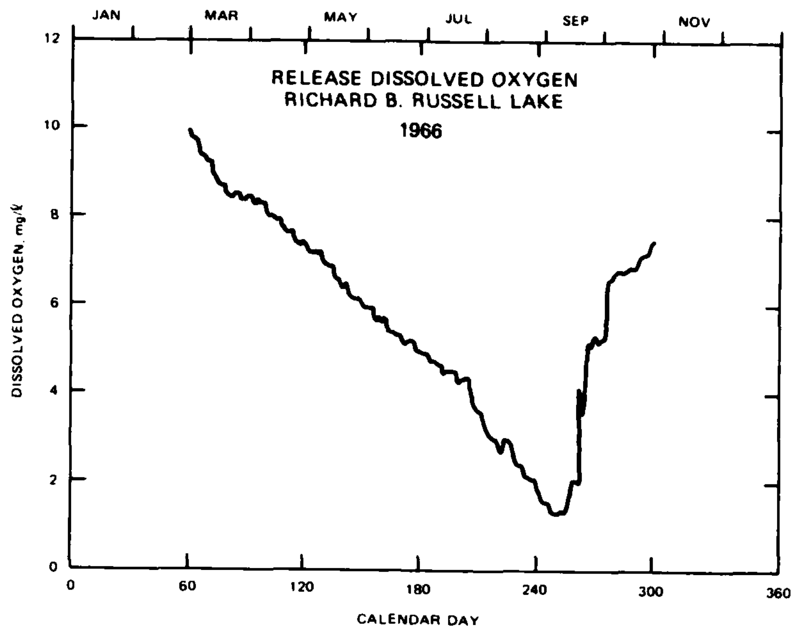


Figure 7. Predicted average daily release dissolved oxygen, RBRR, 1966 (Smith et al. 1981)

rates for 1966 are presented in Figure 8. Although the predicted injection histories are unique for each study year, these results are representative of the results for all simulation years.

44. The temporal injection rate required depends upon a large number of variables; however, at any particular point in time it is essentially dependent upon (a) the vertical temperature and DO distributions and (b) the operational methodology, a dependence which the idealized injection rates reflect (see Figure 8). During maximum stratification, the least favorable DO distribution develops in the metalimnion and hypolimnion. Because the centerlines of the RBRR penstocks are approximately 70 ft below the surface and significant quantities of water are withdrawn from the metalimnion and hypolimnion, during periods of low DO large releases require large oxygen injection rates. Conversely, small releases require smaller injection rates. Furthermore, because DO in the withdrawal zone varies rather slowly, whereas

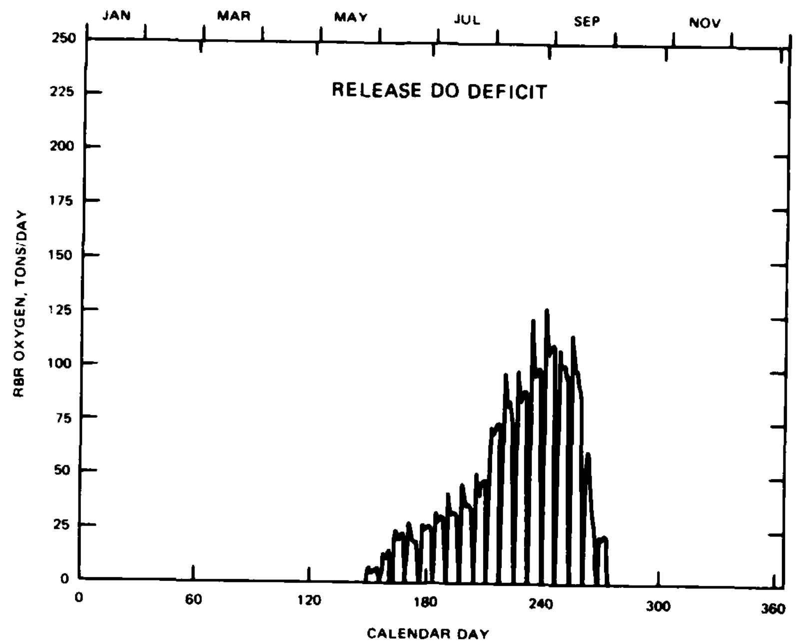


Figure 8. Idealized DO injection requirements for RBRR, 1966 (Smith et al. 1981)

the hydropower operations are highly transient, the daily injection rates computed are often erratic.

45. The actual injection rates required in the prototype may be significantly different from those predicted by the model. The required injected quantity will depend upon the efficiency of the particular injection system in enhancing the DO distribution for the unique criterion chosen (in this case, supplementation of the withdrawal zone DO for release enhancement). Additionally, the efficiency may be functionally dependent upon the rate of injection, density (or temperature) distribution, and the magnitude of the oxygen deficit in the withdrawal zone. An adequate data base does not exist to quantify the efficiency of the proposed RBRR injection system as a function of these various independent variables. As a result, efficiencies on the order of 75 percent were assumed in the design of the RBRR linear injection scheme.

46. As noted, the most critical part of the design of an O_2

injection scheme involves the prediction of the required idealized injection rates because these rates establish the minimum injection requirements. As a result, model calibration and the determination of input data should be carefully executed. The assumption of saturated inflows or an invariant depletion rate of 0.1 mg/ℓ at other projects may lead to erroneous predictions for hypolimnetic DO concentrations. Nix (1981) observed a metalimnetic DO minimum at DeGray Lake, Arkansas. Nix found this phenomenon to be the result of incorporation of hypolimnetic waters, which contained reduced species, into the inflow density current which subsequently traveled into the metalimnion of the lake. The net effect of this mechanism was the depletion of the inflow current DO as it traveled through the lake. In such cases, assumptions of saturated inflow DO concentrations would lead to erroneous predictions of the vertical DO distribution with a one-dimensional (vertical) model having no inflow DO depletion mechanism. Consequently, an oxygen injection system sized from these erroneous results might be dramatically undersized for certain time frames. Thus, when possible, the assumed inflow DO and depletion rate should be based on field data. If field data are not available, the minimum anticipated inflow DO concentrations should be determined and subsequently assumed in the prediction of minimum idealized injection rates.

47. As shown in this section, a one-dimensional numerical simulation model can be used to predict the vertical DO and temperature distributions in the reservoir. From these DO predictions, idealized oxygen requirements needed to meet a predefined oxygen criterion may be obtained. While this procedure does not take into account either the oxygen transfer efficiency of a given system or the ability of said system to place oxygen into a given reservoir withdrawal zone, the use of an analytical approach involving numerical simulation is still an excellent indicator of the possible oxygen requirements for an aeration system under idealized conditions.

PART V: SUMMARY

48. This report has examined elements of the design and operation of hypolimnetic aeration systems. Three basic types of hypolimnetic aerators were identified; literature on each is reviewed in Appendix A. The work of Speece at the CE reservoir at Clarks Hill, in which he tested a series of diffuser systems that injected pure molecular oxygen into the reservoir, was reviewed. Speece recommended a linear diffuser configuration, located approximately 1 mile upstream of the dam, based on this system's ability to place oxygen within the penstock withdrawal zone more effectively for design injection rates than the diffuser rack designs tested. WES personnel conducted field testing of the Speece system in 1977 (Merritt and Leggett 1981) to assess the effects on nitrogen concentrations of pure oxygen injection deep in a reservoir. The results of these tests showed an increase in N_2 concentrations, rather than a decrease due to N_2 stripping as had been suggested in the literature. This increase was postulated to be due to denitrification of entrained bottom sediments in the bubble plume which overshadowed any N_2 stripping. Merritt and Leggett (1981) suggested that decreased oxygen injection rates and greater spread of the diffuser racks could alleviate this problem.

49. Concurrent with the Speece work at Clarks Hill in 1977, RWQB personnel, under the auspices of the Environmental and Water Quality Operational Studies Program, investigated available guidance of hypolimnion aeration/oxygenation system design. From this investigation, an oxygenation system of linear configuration was designed and tested in a short-term study at Clarks Hill in the summer of 1978. Injection rates ranging from 868 to 1670 lb O_2/sq ft of diffuser were tested. Results of these tests showed the system to be quite effective in placing oxygen within the predicted penstock withdrawal zone. An oxygen injection rate of between 1500 and 1600 lb O_2/sq ft of diffuser per day was most effective in placing the absorbed oxygen near the elevation with the maximum withdrawal velocity. Little, if any, thermal destratification and surface disturbance were noted for the conditions tested.

50. A number of design considerations, in addition to placement of injected oxygen within the penstock withdrawal zone, have been identified; adequate estimates for hypolimnetic volume, oxygen consumption rate, and oxygen input capacity are vital to the design of an efficient system. Miscalculation of these inputs may lead to unintentional thermal destratification, poor oxygen transfer efficiency, nitrogen gas supersaturation, and other problems. In an effort to integrate each of these design considerations into a cohesive approach, a numerical simulation technique was discussed which can be used to predict the idealized oxygen requirements (100 percent oxygen absorption efficiency assumed) over a given time frame. The results of this numerical simulation, coupled with oxygen absorption efficiency and the effectiveness of a given system to place oxygen at a given location, can be used to indicate the magnitude of oxygen required for an injection system.

51. At present, no well-defined approach exists for the design of nonproprietary hypolimnetic aeration devices. This is because many new hypolimnetic aeration systems are designed based on existing systems rather than on the requirements of a particular project and therefore provide neither new nor specific design guidance. Moreover, the data collected from existing systems are often neither reliable nor comprehensive enough to provide guidance for new designs. The expansion of quality data acquisition and evaluation could be the key to the creation of more advanced design guidance for future hypolimnetic aeration systems.

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APPENDIX A: LITERATURE REVIEW OF HYPOLIMNETIC AERATION TECHNIQUES

1. Most of the early hypolimnetic aerator development occurred in Europe; there were eleven European hypolimnetic aeration sites by 1974. One of the first uses of hypolimnetic aeration techniques in the United States was in 1970 at Hemlock Lake, Michigan (Fast 1971). Extensive literature reviews of this and the systems that followed have been compiled by Fast and Lorenzen (1976) and Lorenzen and Fast (1977); therefore, only an overview of these hypolimnetic devices will be presented here. The reader is referred to these publications for further detail.

2. Fast and Lorenzen (1976) have suggested the following three catagories of hypolimnetic aeration: (a) mechanical agitation, (b) air injection, and (c) pure oxygen injection. A parameter generally used to characterize these systems is oxygen transfer efficiency, which Tolland (1977) refers to as "oxygen capacity" (OC) and defines as follows:

$$OC = \frac{\text{Net change in hypolimnetic oxygen balance from } t_1 \text{ to } t_2}{\text{Total energy input from } t_1 \text{ to } t_2}$$

where

The total energy input is the energy input to the pump or air compressor, and not the energy delivered to the water by the pump or compressor.

t_1 = time at start of aeration

t_2 = time at end of aeration

The units of OC are pounds of oxygen transferred per kilowatt-hour (lb O_2/kwhr). This criterion will be used to relate system oxygen transfer efficiency in subsequent sections.

Mechanical Agitation Systems

3. The first reported hypolimnetic system, which was used to

aerate Lake Bret, Switzerland (Mercier and Perret 1949), was based on mechanical agitation. Water was withdrawn from the hypolimnion through an intake pipe and discharged into an onshore splash basin where atmospheric aeration occurred (Figure A1). The aerated water was then

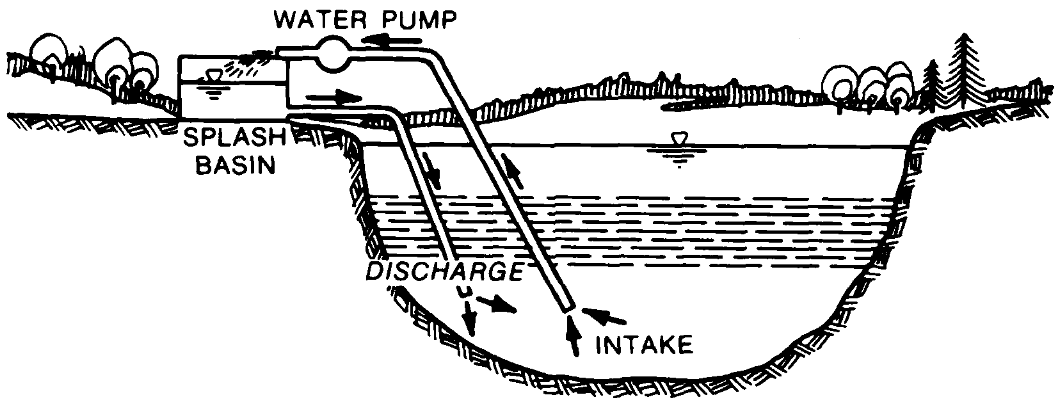

Figure A1. Mechanical aeration system of hypolimnion aeration from Lake Bret, Switzerland

returned to the hypolimnion by gravity flow through a discharge pipe. Although the system was quite inefficient in the transfer of oxygen absorbed per kilowatt-hour expended, it was quite successful in reducing hypolimnetic iron concentrations in the lake.

4. Hess (1975) has also described a mechanical agitation system which was designed to float over the deepest part of a lake. In this design, water was not discharged into a splash basin; rather, a surface agitator was attached to the upper end of an upwelling tube, drawing hypolimnetic water up the tube and aerating it at the surface. Hess had originally operated this system as a full air lift system (described in the next section). Use of a mechanical system, however, showed marked improvement in oxygen transfer to the hypolimnion. Mechanical aerators seem to be a most efficient means of hypolimnetic aeration for shallow lakes. However, for typical Corps lakes where the influence of hydrostatic pressure at depth is large enough to provide a large driving force for gas dissolution, mechanical agitation may prove less efficient than injection systems and will therefore be discussed no further.

Air Injection Systems

5. Two basic types of air injection systems for hypolimnetic aeration are full air lift and partial air lift systems. Full air lift systems are those in which air is injected near the bottom of the aerator. The air and entrained water plume then rises to near the lake's surface where the air separates from the plume and exits to the atmosphere and the water is returned to the hypolimnion. Partial air lift systems are those which aerate and circulate hypolimnetic water by air injection, but do not lift the air/water plume so high; consequently, water is not upwelled to the surface. Both of these systems, and additional systems such as "downflow" systems, merit further discussion.

Full air lift systems

6. Fast (1971) described one of the first full air lift systems (Figure A2). The aerator consisted of concentric upwelling and downwelling pipes: air was released in the center (upwelling) pipe, and the resulting air/water plume rose to the lake surface. Fast, Lorenzen, and Glenn (1976) proposed modifications to this system to increase its efficiency. Use of this system at Hemlock Lake, Michigan, increased hypolimnetic dissolved oxygen concentrations from 0 to 8 mg/ℓ (Fast 1973a).

7. Bernhardt (1974) described a second full air lift design shown in Figure A3, which incorporated separate upwelling and downwelling pipes (contrary to the design discussed above) separated by a horizontal degassing chamber. Use of this aerator in Wahnbach Reservoir, West Germany, yielded one of the greatest oxygen transfer efficiencies yet reported: 2.4 lb O_2/kwhr, with a 50 percent absorption rate. The system also greatly reduced dissolution of iron, manganese, and phosphorus from sediments, while maintaining cold hypolimnion waters.

8. Both Smith, Knauer, and Wirth (1975) and Bengtsson et al. (1972) described hypolimnetic aerators similar in design to that of Bernhardt. The aerator designed by the former, shown in Figure A4, was constructed of inexpensive materials and had flexible outlet tubes and styrofoam flotation. The design also had an upwelling pipe containing a patented helical insert which purportedly increased oxygen transfer

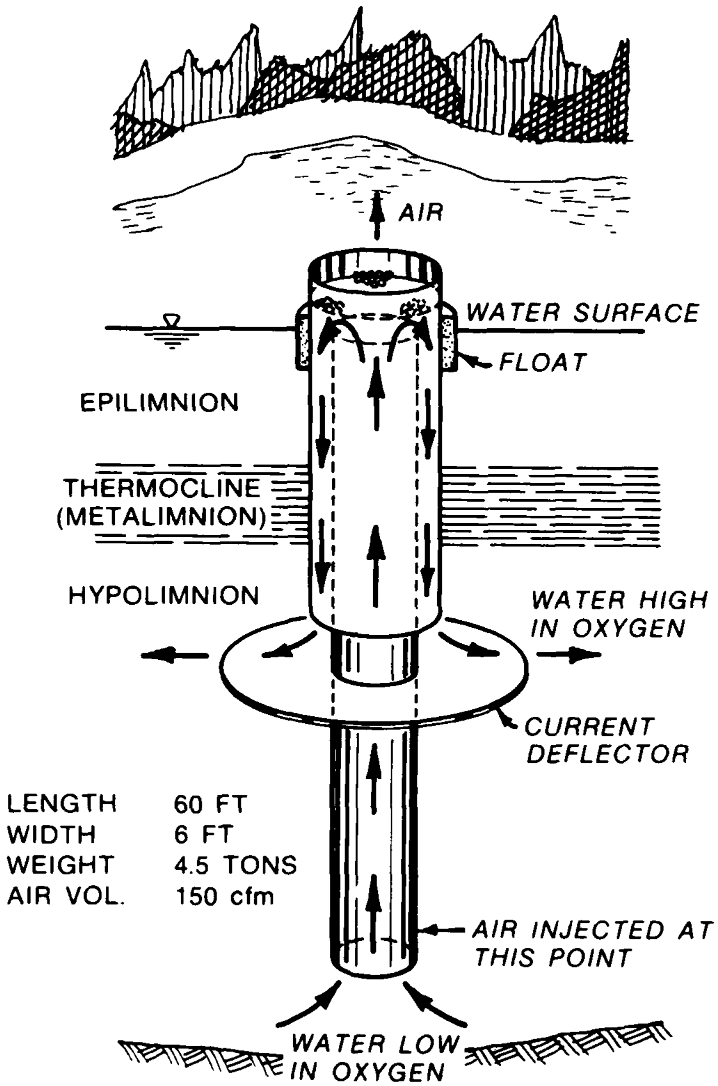

Figure A2. A full air lift, hypolimnetic aeration used in Hemlock Lake, Michigan. Water is upwelled to the surface before it returns the hypolimnion.

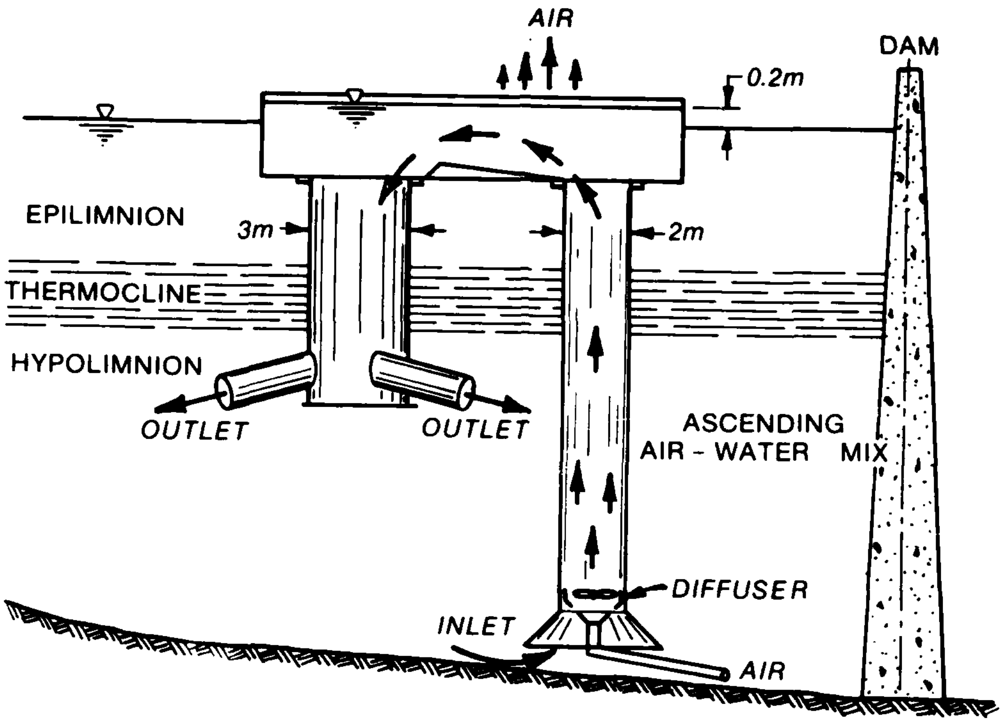

Figure A3. A full air lift hypolimnetic aerator used in Wahnbach Reservoir, West Germany

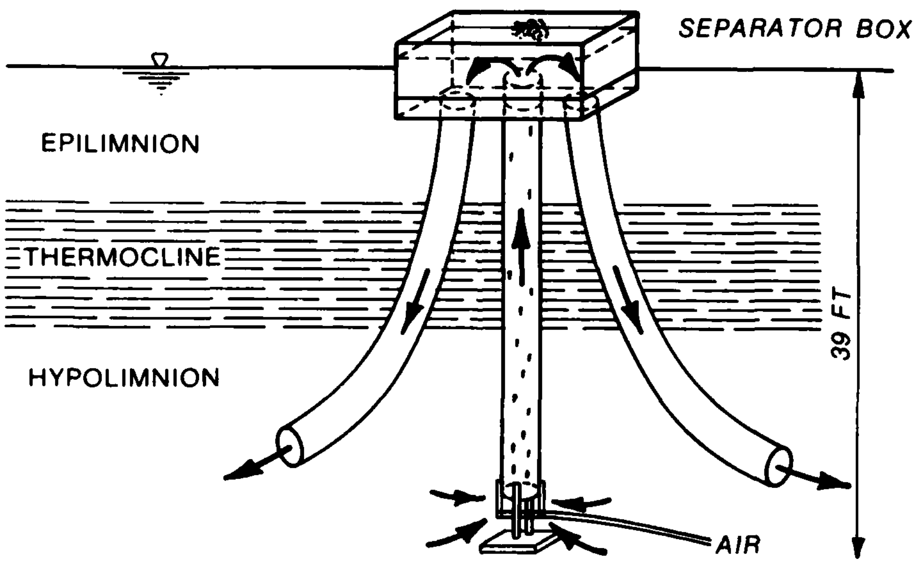

Figure A4. Full air lift hypolimnetic aerator used in Mirror and Larson Lakes, Wisconsin

efficiency. Bengtsson et al. (1972), described two full air lift systems which were used to aerate Lakes Tullingesjön, and Järlasjön, Sweden. The Lake Tullingesjön aerator, shown in Figure A5, had a 1.3-ft-diam

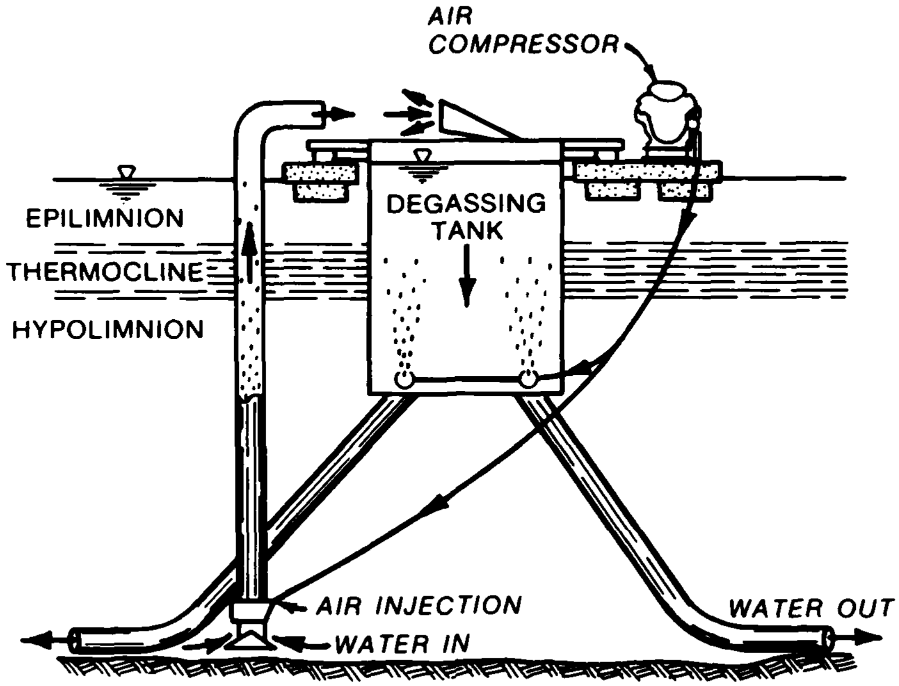

Figure A5. A full air lift hypolimnetic aerator used in Lake Tullingesjön, Sweden

upwelling tube which discharged horizontally into a degassing chamber and four 1.6-ft-diam outlet pipes for flow distribution; approximately 530 SCFM of compressed air were injected. Although the lake was aerated for 2-1/2 months, hypolimnetic dissolved oxygen concentrations failed to increase above 0.0 mg/ℓ. The Lake Järlasjön system (Figure A6) differed from that of Lake Tullingesjön in that (a) the upwelling pipe was 2 ft in diameter and discharged in a vertical overflow fashion into the degassing chamber, (b) ten outlet pipes of 1.6-ft diameter were used, and (c) 789 SCFM of air were injected; hypolimnion dissolved oxygen concentrations of more than 8 mg/ℓ were attained. The efficiency of each of these two Swedish systems, however, was greatly reduced due to the very high air injection rates coupled with the relatively small diameter of the upwelling pipe.

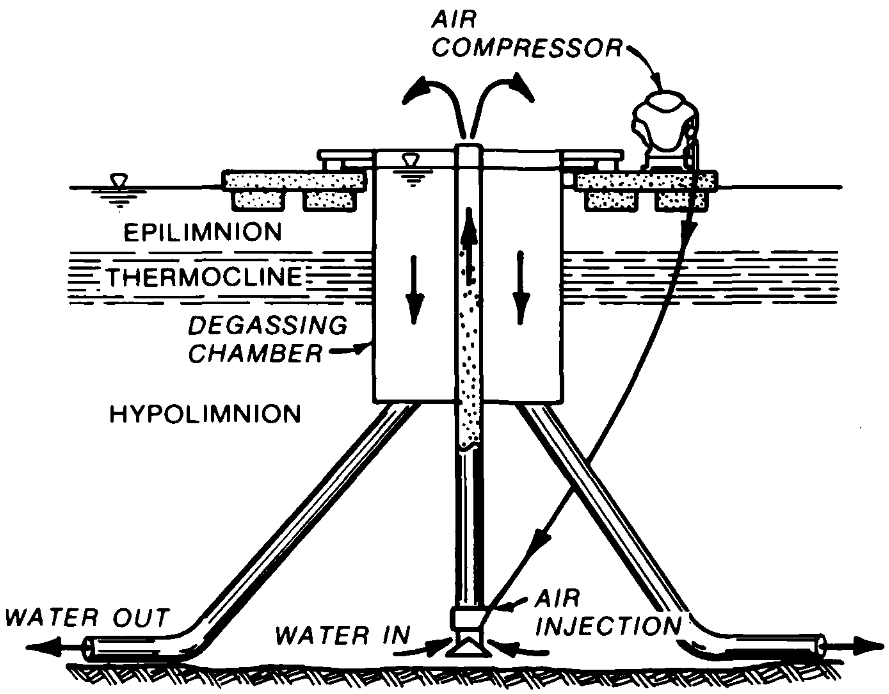

Figure A6. Full air lift, hypolimnetic aerator used at Lake Järlasjön, Sweden

Partial air lift systems

9. As stated in paragraph 4 of this appendix, partial air lift systems aerate hypolimnetic water without transporting the water to the surface. Bjork (1974) and Fast, Dorr, and Rosen (1975) described European and North American operation of these systems, respectively, in detail. Figure A7 shows a system in which air released from a diffuser at the bottom of the aerator caused a hypolimnetic water plume to upwell through a 15-ft-high, 8-ft-diam chamber. At the top of this chamber the waste air was vented to the atmosphere and the water flowed through six outlet pipes. A waste gas valve maintained a pressurized pocket of gas at the top of the aerator to check the release of water through the venting pipe. Fast (1973b) reported that this system provided 1.2 lb O_2/kwhr to the hypolimnion of Lake Waccabuc, N. Y., with 10.6 percent of injected oxygen absorbed. Fast, Dorr, and Rosen (1975), however, reported that the use of this system resulted in significant increases in dissolved N_2 saturations with respect to surface pressures.

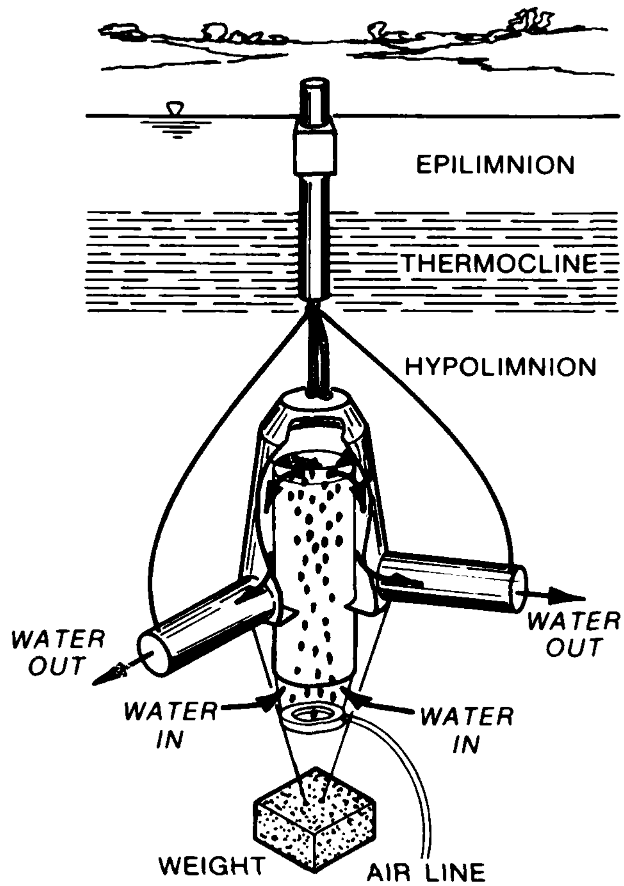

Figure A7. A hypolimnetic aerator used in Lake Waccabuc, N. Y., hypolimnetic waters are upwelled only a short distance by air injection

10. Speece, Rayyan, and Givler (1975) suggested a partial air lift system shown in Figure A8, which is similar to the Lake Waccabuc system discussed above except that it has no valve to check release of aerated waters through the vent pipe.

Other air lift systems

11. Two additional systems exist which represent variations on the two main air injection system types. The first is a "standpipe" aerator described by Bernhardt (1967), the original aerator used at Wahnbach Reservoir, West Germany, and later replaced by the full air lift design of Bernhardt discussed in paragraph 7 of this appendix. The structural design of the system (see Figure A9) resembles that of

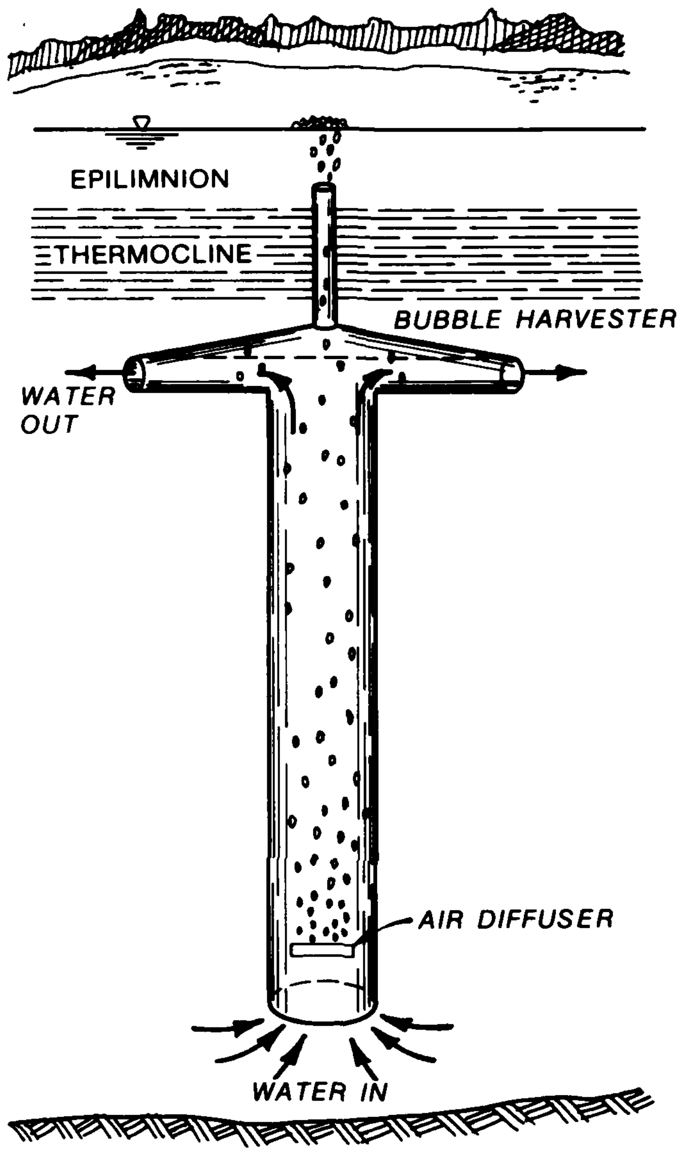

Figure A8. A proposed partial air lift system of hypolimnetic aeration

a full air lift system; however, most of the water is upwelled only to the level of the outlet arms rather than to the surface. Conceptually, this standpipe device is very similar to a partial air lift system; nonetheless, it achieved an oxygen transfer efficiency of 2.1 lb O_2/kwhr, with an injection rate of 142 SCFM and an oxygen absorption efficiency of 50 percent.

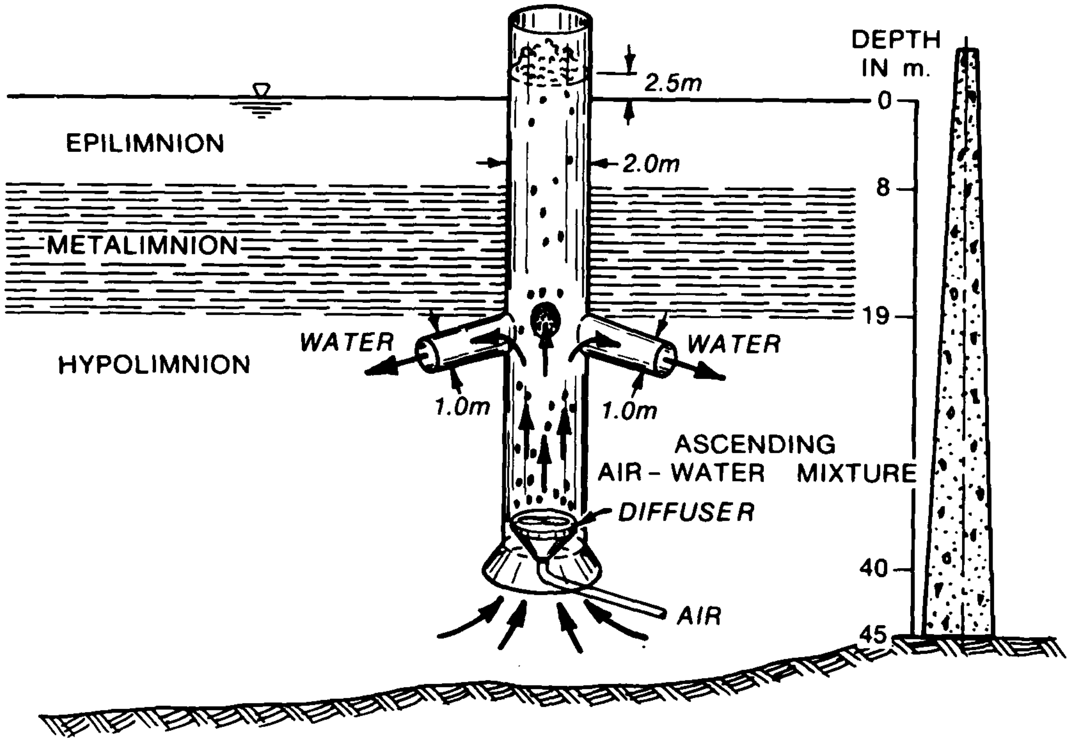

Figure A9. Standpipe hypolimnetic aerator used at Wahnbach Reservoir, West Germany

12. Speece has described a second group of systems which may be classified as "downflow air injection" systems. The basis for these systems (Speece 1970) is a mechanical pump which transports water downward in a vertical pipe while air is injected below the pump. The downward velocity of the water, which is greater than the bubble-rise velocity, sweeps the air downward into the hypolimnion where the air and water separate. Speece's first system (Speece 1971) incorporated both downflow and air lift features as shown in Figure A10. A subsequent system (Speece, Rayyan, and Givler 1975) was similar in design but allowed venting of waste gases to the atmosphere. N_2 supersaturation could also be of considerable concern for potential fisheries impact.

Pure Oxygen Injection Systems

13. Side-stream pumping (SSP) was one of the first successful

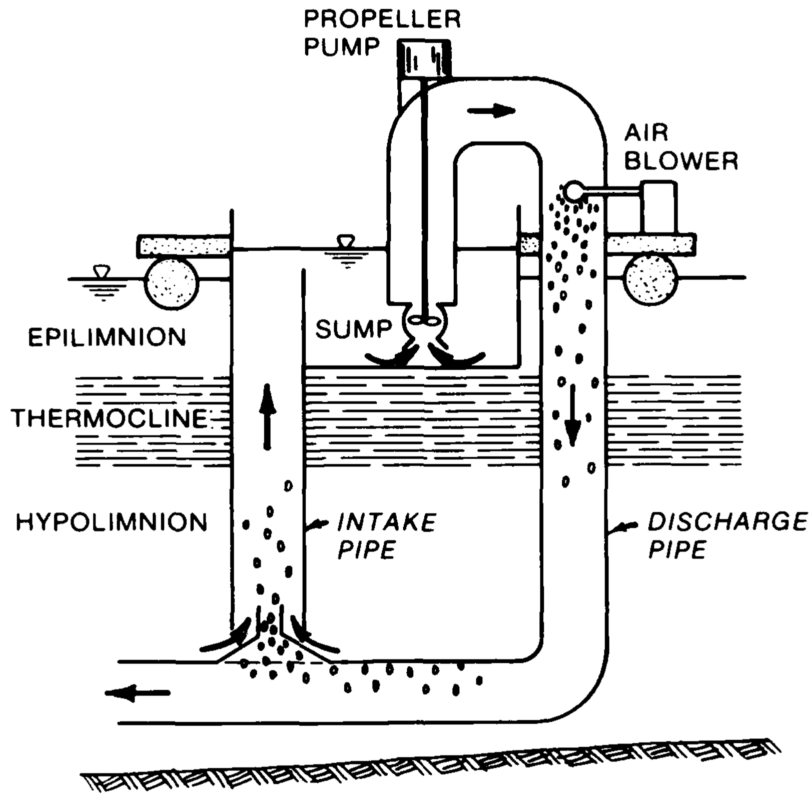

Figure A10. A proposed downflow air injection system which also incorporates the air lift feature

means of hypolimnetic aeration with pure oxygen (also referred to as hypolimnion oxygenation) as demonstrated by Fast, Overholtz, and Tubb (1975). The system, an example of which is shown in Figure A11, is conceptually simple. Hypolimnetic waters are withdrawn through a pipe by a shore-based pump and then oxygenated in the discharge line under high pressure. The combination of pure oxygen and high discharge line pressure results in the oxygen being almost totally dissolved before the hypolimnetic waters are returned into the hypolimnion. Fast, Overholtz, and Tubb (1975) successfully used this system at Ottoville Quarry, Ohio. Oxygen concentrations increased from zero to 8 mg/ℓ in 1973 and to 21.5 mg/ℓ in 1974 (Overholtz 1975). Hypolimnetic temperatures were observed to increase 5° C and 9° C in 1973 and 1974, respectively, due to mixing induced as a result of the oxygenation procedure. Fast and

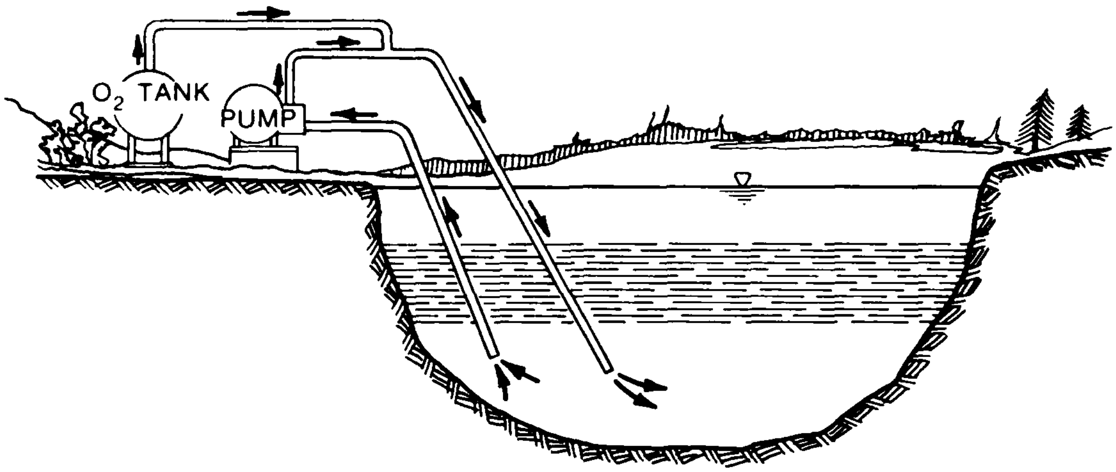

Figure A11. Schematic view of the hypolimnion oxygenation system used at Ottoville Quarry, Ohio, and Attica Reservoir, New York (the cross-hatched area represents the thermocline)

Lorenzen (1976) computed an oxygen absorption efficiency for this system of 0.5 lb O_2/kwhr, assuming an energy consumption rate of 800 kwhr/ton of liquid oxygen.

14. A second SSP system was tried unsuccessfully at Attica Reservoir, New York (Fast, Overholtz, and Tubb 1975). Operation of the system resulted in rapid destratification of the reservoir, although an average of only 1 percent of the hypolimnetic volume was pumped daily. Lorenzen and Fast (1977) surmise that the exit velocity from the discharge pipe may have been so high that destratification of the reservoir by jet mixing may have occurred.

15. Speece has proposed the following two methods for hypolimnetic oxygenation: (a) the use of pure oxygen rather than air in the downflow aerator described in paragraph 12 (Speece 1970, 1971; Speece, Rayyan, and Givler 1975) and (b) a system which employs the injection of pure oxygen from coarse-bubble diffusers at some depth within the hypolimnion (Speece 1971, 1973, 1975). A system of the latter type was used by Speece for oxygenation of Clarks Hill Reservoir, South Carolina (the results of the Clarks Hill investigation are reviewed in the main text of this report). Whipple et al. (1975) designed a hypolimnetic oxygenation system (Figure A12) tested at Spruce Run Reservoir, New Jersey, that was similar

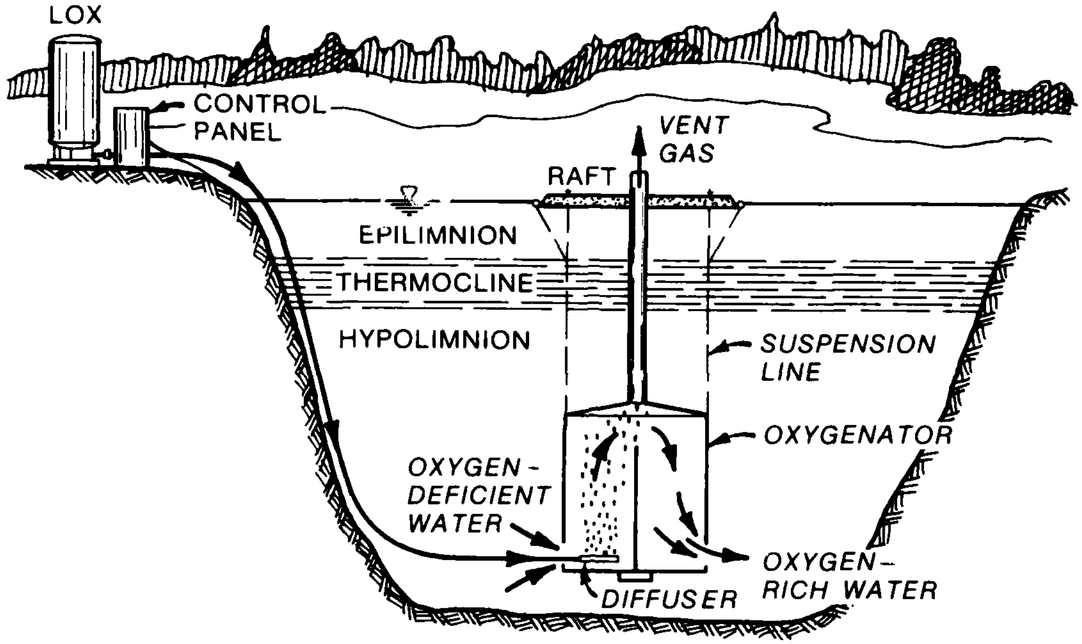

Figure A12. Hypolimnetic oxygenation system used at Spruce Run Reservoir, New Jersey

to the partial air lift designs described in paragraph 11. Unfortunately, the operation of the system was highly unsuccessful. This failure may have been partially due to an inadequate experimental design (Fast and Lorenzen 1976).

16. Seppänen (1974) reported the design and operation of an aerator, similar to the Speece (1971) downflow injection system, for ice cover operations (Figure A13) on two Finnish lakes. Seppänen reported gas pocket formation in the top of the tube's arch; bubble coalescence may have promoted this problem.

System Efficiency

17. As stated in paragraph 2 of this appendix, oxygen transfer efficiency is a primary means by which hypolimnetic aeration efficiency is measured. Of the hypolimnetic aeration systems discussed, the air injection aerators (full and partial air lift systems) have the highest oxygen transfer efficiencies per unit of energy expended in pumping.

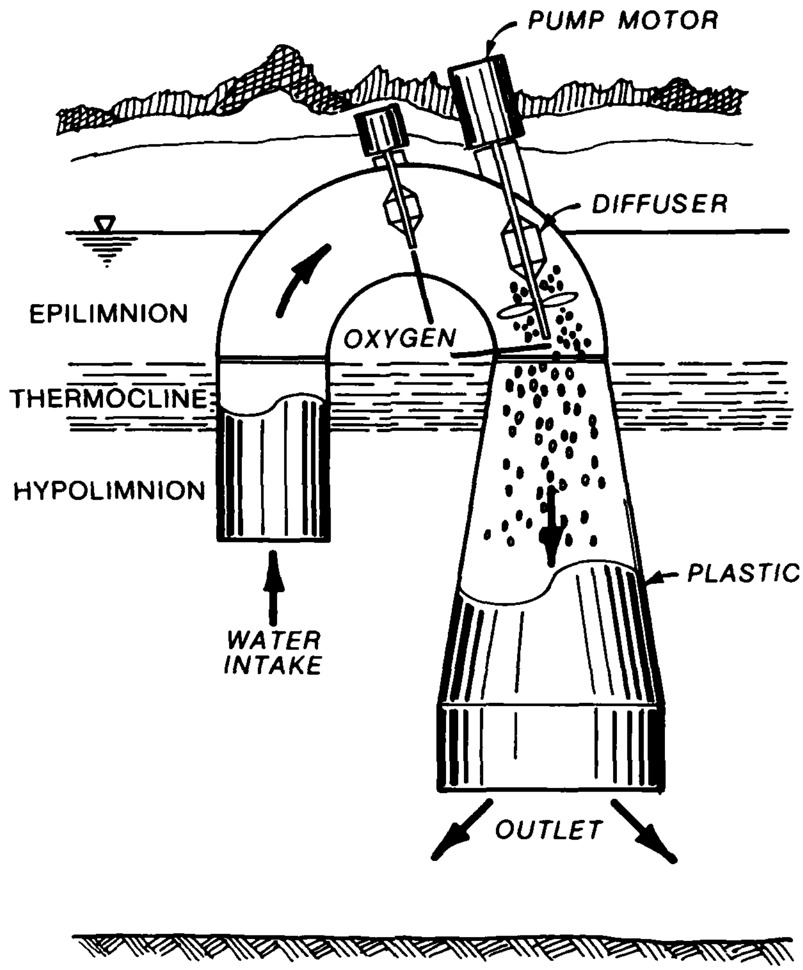

Figure A13. Isteri oxygen injection system used to oxygenate under the ice in Lakes Hemtrask and Kiteenjarni, Finland

Table A1 lists the oxygen efficiencies as well as the air flow rates, duration of aeration, and physical data of nine hypolimnetic systems. The table reproduces information compiled by Lorenzen and Fast (1977) and Pastorak, Lorenzen, and Ginn (1982).

18. Table A1 shows that the 1974 Bernhardt full air lift aerator Wahnbach II maintained the highest oxygen balance over time per unit of energy expended. The 1967 Bernhardt design (Wahnbach I), which was operated with a similar efficiency, is more nearly a partial air lift system although it is listed as a full air lift device. Comparison of

full and partial air lift systems is limited by the bulk and site-specific nature of the data from these systems. Still, some investigators such as Lorenzen and Fast (1977) have suggested that partial air lift designs appear to be less efficient than full air lift systems. Although they have greater effluent dissolved oxygen concentrations, they aerate less water volume and have less total bubble contact time and less total oxygen dissolved than full air lift systems. Further, a majority of the energy required to compress the air and pump it to depth is often lost due to the venting of large quantities of waste gas. Moreover, in a study of comparative costs for the siting of a hypolimnetic aerator at San Vincente Reservoir, California, Fast et al. (1976) found a full air lift design to be the most cost-effective alternative when compared to a partial air lift or an oxygen injection (i.e. side-stream pumping) system.

Table A1

Oxygen Transfer Efficiencies for Nine Hypolimnetic Aeration/Oxygenation Systems (data from Lorenzen and Fast 1977 and Pastorok et al. 1982)

Site of Aeration	Air/O_2 Injection Rate, cfm	Oxygen Transfer Efficiency lbs O_2/kwhr	Oxygen Absorption %	Ambient Oxygen Concentration	Reservoir Aerator Depth, ft Max	Min	Mean	Aeration Duration Month	Reservoir Volume acre-ft	Source of Data
Full Air Lift System										
Wahnbach I	141.9	2.1	50	<4	141	63	--	4.3	33,745	Bernhardt (1967)
Wahnbach II	317.8	2.4	50	<4	141	63	--	4-60	33,745	Bernhardt (1974)
Mirror	15.9	0.7	9-14	0	43	25	42	1-2	324	Smith et al. (1975)
Larson	15.9	0.7	14-23	<7.5	39	13	39	1.5-5	153	Smith et al. (1975)
Jarlasjön	805.1	0.7	10.3	0	79	31	79	4.2	6,323	Bengtsson et al. (1972)
Partial Air Lift System										
Waccabuc	280.0	1.2	10.6	4	43	--	43	3	31,285	Fast (1973a,b)
Oxygen Injection System										
Ottoville	3.9	0.5	>95	>8	59	--	59	3	51	Fast et al. (1975b)
Spruce Run 1973	5.3	0.8-1.0	30-41	<0.5	43	--	40	2	--	Whipple et al. (1975)
Spruce Run 1974	5.3	0.4-0.8	18-30	<4	43	--	40	5	--	Whipple et al. (1975)

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